

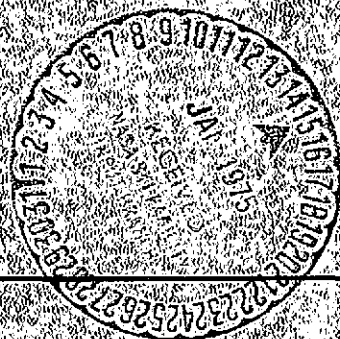
ELECTROCHEMICAL CARBON DIOXIDE CONCENTRATOR SUBSYSTEM MATH MODEL

FINAL REPORT

by

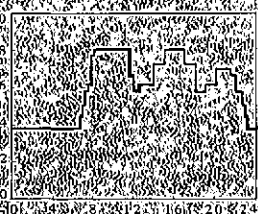
R.D. Marshall, J.N. Carlson
and F.H. Schubert

September, 1974



MATH MODEL SOLUTION SEQUENCE

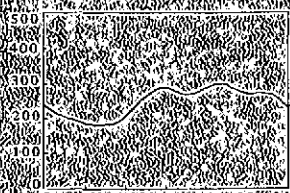
INPUTS



- CO2 Generation Profile
- Stream Input Parameters
- Number of Cells
- Cabin Volume
- Control Parameters
- Weight Penalty Factors

COMPUTER PROGRAM

OUTPUTS



- Daily CO2 Profile
- Subsystem Equivalent Weight
- Subsystem Power Consumption
- O2 Consumption Profile
- Cell Performance Parameters
- Stream Output Parameters

Prepared Under Contract No. NAS2 - 6478

by

Life Systems, Inc.

Cleveland, Ohio 44122

for

AMES RESEARCH CENTER

National Aeronautics & Space Administration

ER-220-6

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CONCENTRATOR SUBSYSTEM
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FOREWORD

The development activity described herein was conducted by Life Systems during the period November, 1973 to September, 1974 as part of NASA Contract NAS2-6478. The Program Manager was Richard D. Marshall. Technical support was provided as follows:

Jan Carlson - Computer simulation model

Tim Hallick - Test program

Franz Schubert - Model analyses

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SUMMARY

A steady-state computer simulation model has been developed to describe the performance of the total Six-Man, Self-Contained Electrochemical Carbon Dioxide Concentrator Subsystem, referred to as CS-6, as built for the Air Revitalization Group (ARG) of Space Station Prototype (SSP). The math model combines expressions describing the performance of the Electrochemical Depolarized Carbon Dioxide Concentrator (EDC) cells and modules previously developed with expressions describing the performance of the other major CS-6 components. The model is capable of accurately predicting CS-6 performance over EDC operating ranges and the computer simulation results agree with experimental data obtained over the prediction range.

Two computer programs were written utilizing the mathematical expressions developed to describe CS-6 performance. The first computer program, referred to as the CS-6 Base Program, calculates the steady-state performance characteristics of the CS-6 subsystem and its components, including intercomponent and subsystem fluid interface parameters, component and subsystem power and heat generation, and subsystem equivalent weight. The second program, referred to as the CS-6 Cabin $p\text{CO}_2$ Simulation Program, utilizes the CS-6 Base Program with minor modifications as a subroutine to describe the daily cabin partial pressure of carbon dioxide ($p\text{CO}_2$) profile that would result from using the CS-6 as the carbon dioxide (CO_2) removal subsystem in a simulated spacecraft air revitalization application. The program takes a daily CO_2 generation profile and cabin volume, and calculates and subtracts the CO_2 removal rate to arrive at the daily cabin $p\text{CO}_2$ profile.

Seven experiments were conducted in support of the math model to (1) establish the performance characteristics of the CS-6 and of the individual CS-6 subsystem components and (2) verify the predictability of the two computer programs. The experiments performed characterized the electrochemical modules, the process air blowers, the cooling air blowers, the hydrogen (H_2) flow sensor and distribution mountings, the primary controller, the emergency controller, and the steady-state CS-6 intercomponent interface parameters.

INTRODUCTION

In parallel to the development of an Electrochemical Carbon Dioxide Concentrator Subsystem, Life Systems, Inc. had developed a steady-state computer simulation model to predict the performance of the Electrochemical Depolarized Carbon Dioxide Concentrator (EDC) cells and modules over a wide range of operating conditions. (1) The objectives of the present program were to (1) expand this existing model to predict the performance characteristics of the total Six-Man, Self-Contained Electrochemical Carbon Dioxide Concentrator Subsystem, referred to as the CS-6, as built for the Air Revitalization Group (ARG) of Space Station Prototype (SSP), and (2) develop two computer programs using the expanded model to predict the steady-state performance characteristics of the CS-6 (first program) and to determine the daily partial pressure of carbon dioxide ($p\text{CO}_2$)

(1) All references cited are listed at the end of the report.

profile for a given spacecraft cabin volume and carbon dioxide (CO_2) generation profile (second program).

To accomplish the objectives of the program, the program was organized into three tasks and a program management function. The specific objectives of these tasks were to:

1. Perform supporting experimentation to characterize subsystem components and to verify the performance predictions of the expanded math model.
2. Prepare the CS-6 Base Program by expanding the EDC computer simulation model to enable predicting the steady-state performance characteristics of the CS-6 as a total subsystem.
3. Prepare the CS-6 Cabin pCO_2 Simulation Program to predict CS-6 response to a specified, repetitive CO_2 generation profile for a given time period and a specified cabin volume. The pCO_2 Simulation Program allows CS-6 performance to be characterized as a function of time for constant input parameters, current and process air flow rate (Control Mode A), and variable input control parameters for current and air flow rates as a function of cabin pCO_2 (Control Mode B).

The CS-6 Subsystem and component testing was completed and the results were used to develop the mathematical expressions describing CS-6 performance. These experimentally obtained correlations were then combined with subsystem and component mass and energy balances to write the CS-6 Base Program. The CS-6 Cabin pCO_2 Simulation Program was then prepared using the Base Program as a subroutine to calculate CS-6 performance parameters as a function of time.

CS-6 SUBSYSTEM

The CS-6 was designed specifically as the Carbon Dioxide Collection Subsystem (CCS) for the SSP program. The function of the CS-6 is to remove 6.0 kg (13.2 lb)/day of CO_2 from the cabin atmosphere and deliver the CO_2 premixed with hydrogen (H_2) to the CO_2 Reduction Subsystem. The major components of the CS-6 are the electrochemical modules that actually perform the CO_2 removal function and the supporting hardware required to manifold the process gas streams (blowers, valves, ducting, etc.) and control the CO_2 removal process. The detailed schematic of the CS-6 subsystem is presented in Figure 1. The design specifications for the CS-6 are presented in Table 1. A detailed description of the operation and components of the CS-6 has been documented previously in literature.^(2,3,4) The description of the CS-6 subsystem that follows details how the subsystem process streams and hardware were viewed for math modeling purposes.

Process Streams

A simplified functional schematic of the CS-6 subsystem is given in Figure 2. The actual arrangement of the CS-6 hardware is in two identical process loops.

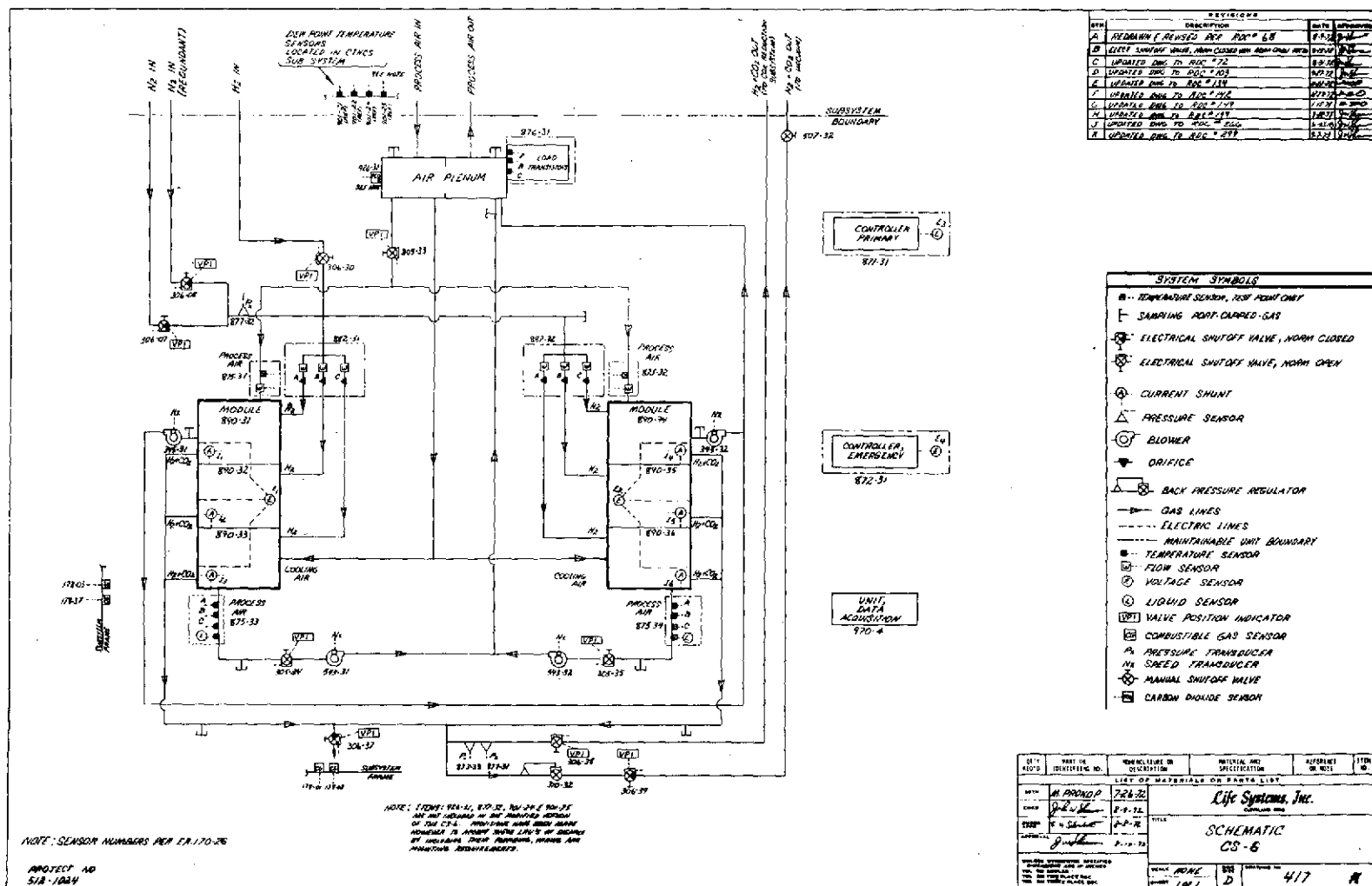


FIGURE 1 CS-6 SCHEMATIC

TABLE 1 CS-6 DESIGN SPECIFICATIONS

Number of Crew (Continuous)	6
CO ₂ Removal Requirements	
Nominal (48-Hr Average), kg/d (Lb/Day)	6.0 (13.2)
Maximum (4-Hr Duration), kg/d (Lb/Day)	9.3 (20.4)
Cabin Atmosphere	
Total Pressure, kN/m ² (Psia)	101-105 (14.7-15.2)
Temperature, K (F)	291-297 (65-75)
Dew Point Temperature, K (F)	281-287 (46-57)
O ₂ Partial Pressure, kN/m ² (Psia)	21.0-22.6 (3.04-3.28)
CO ₂ Partial Pressure	
Nominal, N/m ² (mm Hg)	<400 (<3)
Operating Range, N/m ² (mm Hg)	200-400 (1.5-3)
Diluent	Air Constituents
Process Air	
Total Pressure, N/m ² (Inch Water)	Ambient + 1495 (+ 6)
Temperature, K (F)	Dew Point + 3.34 (+ 6)
Dew Point Temperature, K (F)	281-283 (46-50)
O ₂ Partial Pressure, kN/m ² (Psia)	21.0-22.6 (3.04-3.28)
CO ₂ Partial Pressure	
Nominal, N/m ² (mm Hg)	381 (2.86)
Operating Range, N/m ² (mm Hg)	200-385 (1.5-2.89)
Diluent	Air Constituents
Cooling Air	
Total Pressure, N/m ² (Inch Water)	Ambient + 1495 (+ 6)
Temperature, K (F)	Process Air Dew Point + 3.34 (+ 6)
H ₂ Supply	
Total Pressure, kN/m ² (Psia)	<138 (<20)
Temperature, K (F)	291-297 (65-75)
Dew Point Temperature, K (F)	283-289 (50-60)
H ₂ + CO ₂ Exhaust	
Total Pressure	Ambient
Electrical Power	106-122 VRMS, 400 ±40 Hz, 3Ø, 5 Wire
Purge Supply	
Type Gas	N ₂
Pressure, kN/m ² (Psia)	310 (45)
Packaging	Self-Contained
Gravity	0-1 g
Allowable Downtime	8-12 Hr
Duty Cycle	Variable ^(a)

(a) The SSP Specification cites potential orbital On/Off cyclic operation.

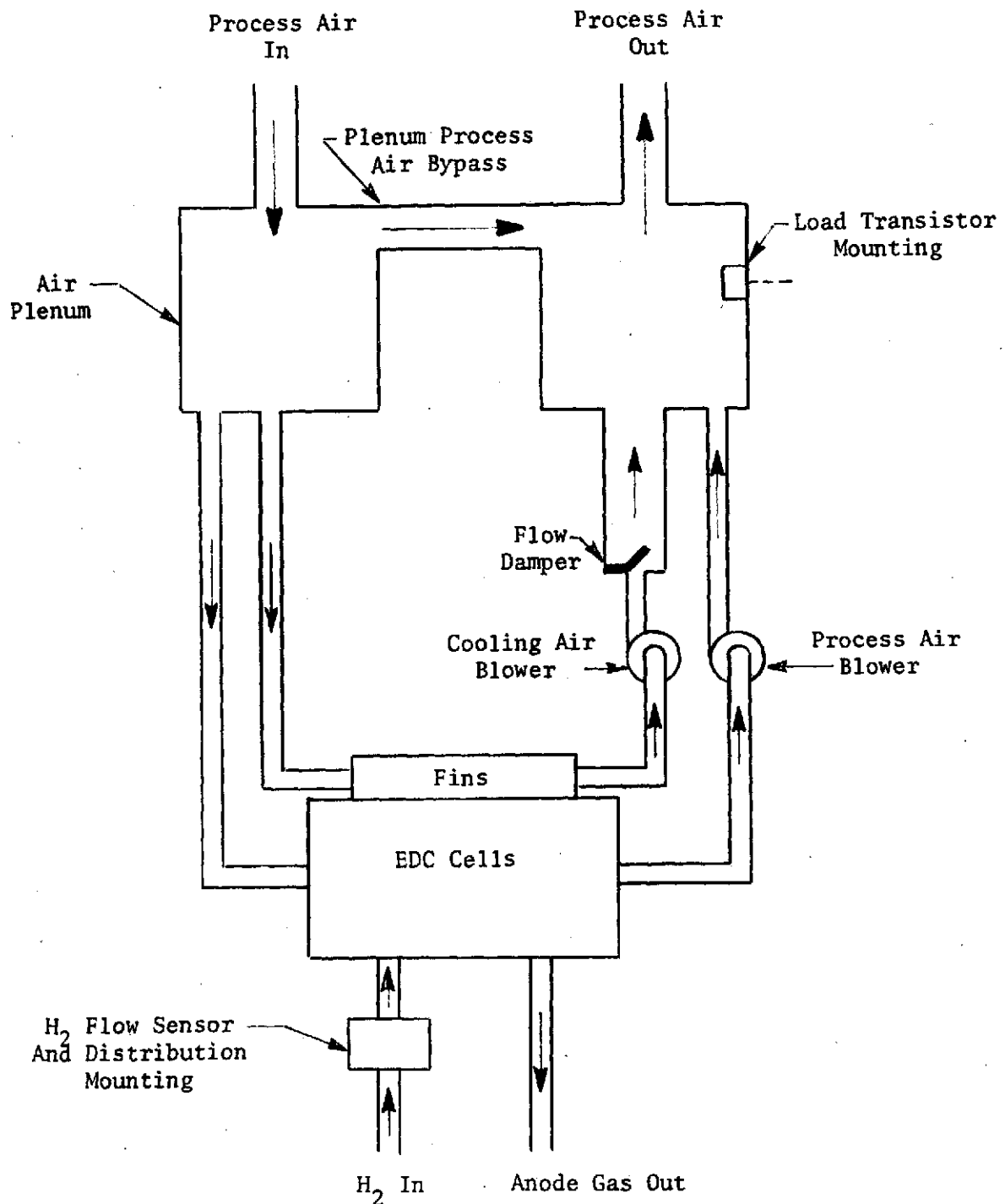


FIGURE 2 SIMPLIFIED CS-6 FUNCTIONAL BLOCK DIAGRAM

Each loop has its own process air blower, cooling air blower, H_2 flow sensor and distribution mounting, and three EDC modules. For math modeling purposes, both process loops have the same performance characteristics. The simplification of the subsystem hardware shown in Figure 2 reduces the number of computer program outputs (and computer running time) required to describe CS-6 performance without sacrificing model accuracy.

Process air is drawn from the inlet portion of the plenum through the cathode compartments of the electrochemical cells by the process air blowers. Carbon dioxide is removed from the flowing air stream as it passes over the cathode of the EDC cells. The CO_2 -depleted air stream is then returned to the outlet portion of the plenum.² Likewise, cooling air is drawn by the cooling air blowers from the inlet portion of the plenum over the external fin portion of the electrochemical cells. The cooling air, at a higher temperature, is then returned to the outlet portion of the plenum. Excess process air entering the plenum bypasses the subsystem through the plenum air bypass.

Process H_2 used by the electrochemical modules is manifolded to each module through two identical H_2 sensor and flow distribution mounting blocks. Each flow distribution block² equally manifoldes H_2 flow to each of the three 16-cell modules it serves. The H_2 flows in series through the 16 cells of each module.

Hardware Description

The CS-6 subsystem components were divided into Line Replaceable Units (LRUs). The list of the major subsystem LRUs is presented in Table 2. Front and rear photographs of the CS-6 showing the LRUs are presented in Figures 3 and 4, respectively. Each of the LRUs were analyzed for power required, heat generation, effect on gas stream pressure, temperature and composition, and actual component weight for use in the total subsystem equivalent weight determination. Those components that did not require power^(a), generate heat, or affect gas stream parameters during steady-state operation were not modeled. The LRUs not modeled were the process air sensors, the electric shutoff valves, the backpressure regulator, the pressure sensors, the combustible gas sensors, and the manual shutoff valve. The electrical, motor-driven shutoff valves are not actuated during normal operation and hence require no power and generate no heat. Their actuation only occurs during mode transitions (such as normal to shutdown); however, even then the energy requirement is less than 57.5 J (0.016 watt-hours). All other components were characterized for use in the computer simulation model. A brief description of those LRUs that were modeled follows.

Electrochemical Modules

The CS-6 contains six electrochemical modules. Each of the electrochemical modules contains 16 cells. The electrochemical modules perform the actual CO_2 removal process by removing CO_2 from the cathode air stream and concentrating it

^(a) All sensor power required is accounted for in the controllers.

TABLE 2 CS-6 LINE REPLACEABLE UNITS

	<u>SSP Item No.</u>	<u>Qty. Req'd</u>
Module, Electrochemical	890	6
Blower, Process Air	543	2
Blower, Cooling Air	345	2
Sensor, Process Air	875	4
Valve, Shutoff, Electric	305	3
Valve, Shutoff, Electric	306	6
Mounting, H ₂ Flow Sensor & Distribution	882	2
Valve, Regulator, Backpressure	310	1
Sensor, Pressure	877	3
Sensor, Combustible Gas	178	4
Controller, Primary	871	1
Controller, Emergency	872	1
Unit, Data Acquisition	970	1
Mounting, Load Transistor	876	1
Valve, Shutoff, Manual	507	1

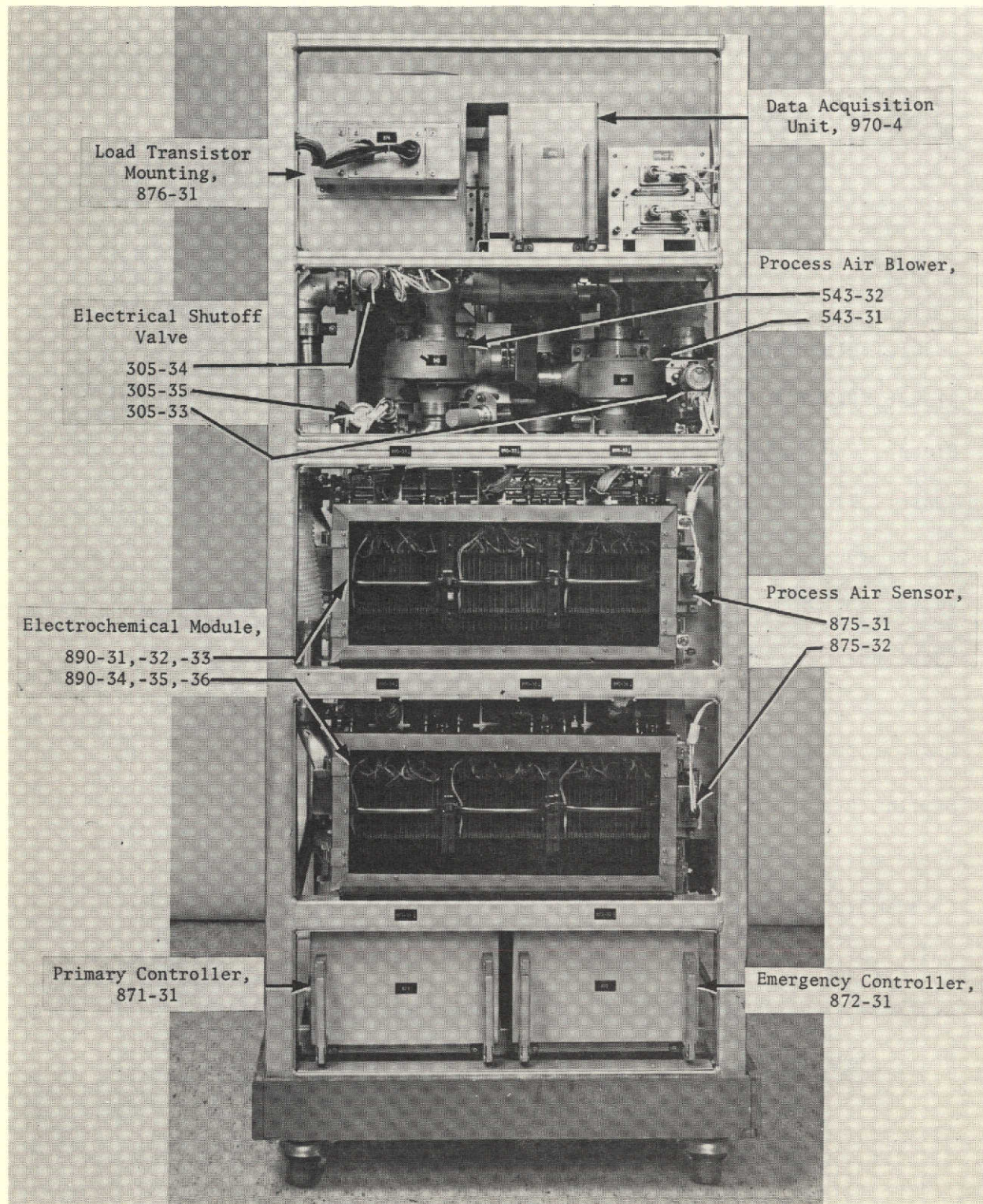


FIGURE 3 CS-6 SUBSYSTEM (FRONT)

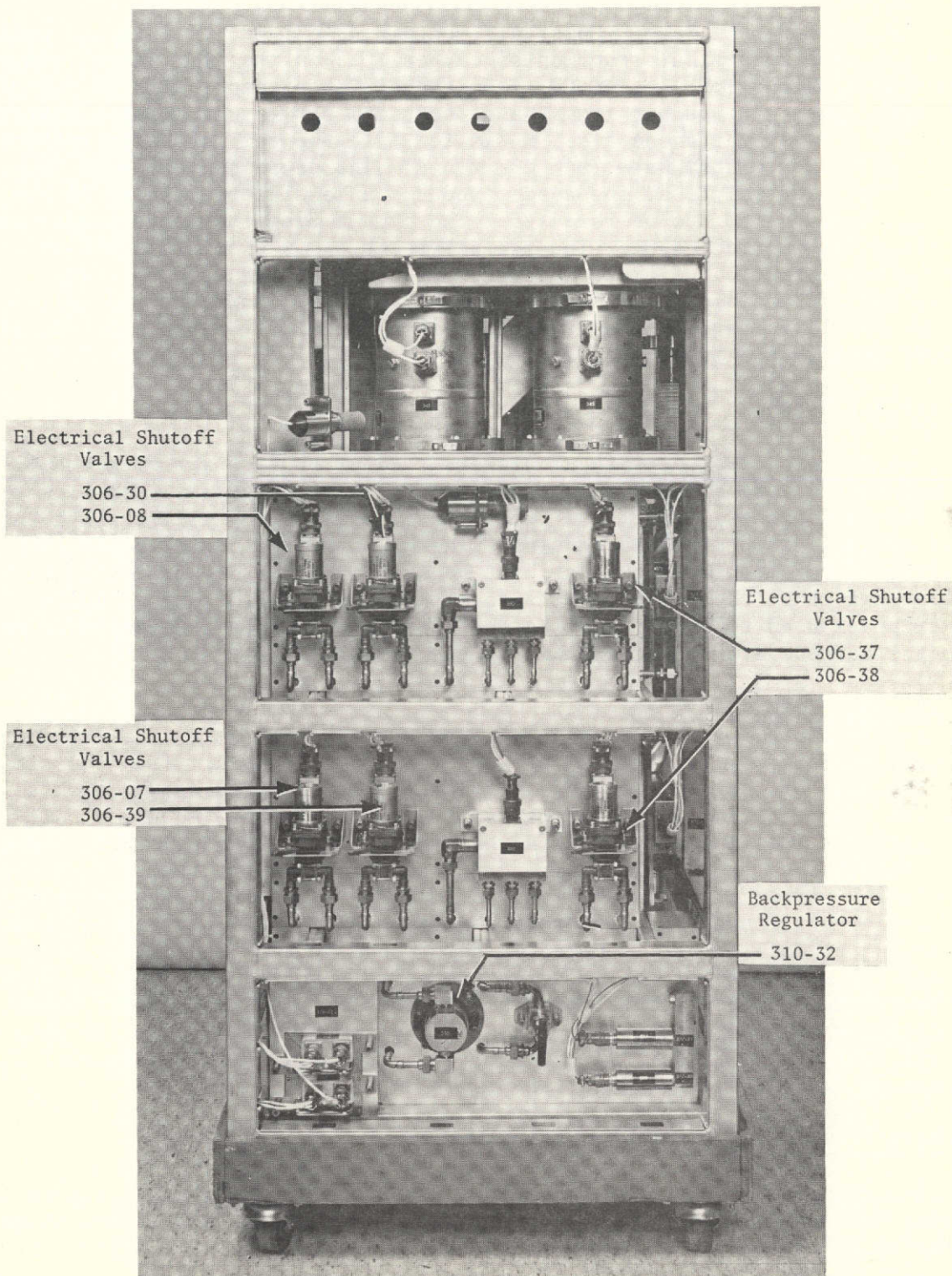


FIGURE 4 CS-6 SUBSYSTEM (BACK)

into the process H_2 stream. Moist air containing CO_2 is fed into the cathode where the electrochemical reaction of oxygen (O_2) in the air, water, and electrons form hydroxyl ions (OH^-). The CO_2 from the air then reacts with OH^- forming carbonate ions. The output from the cathode compartment is moist air at a reduced pCO_2 . At the anode side, H_2 is fed into the cell and electrochemically reacts with OH^- to form water and electrons. The decrease in the OH^- concentration in the electrolyte at the anode produces an equilibrium shift in the electrolyte which causes CO_2 to be released. The output from the anode compartment is CO_2 mixed with unreacted H_2 . The overall reaction is exothermic and is accompanied by the formation of electrical energy. The CO_2 removal process is primarily a function of the inlet air pCO_2 , air flow rate, cell current, and cell moisture balance. Cell voltage and power production is primarily a function of cell current density and temperature.

Process Air Blowers

The CS-6 contains two centrifugal blowers to draw process air from the plenum through the cathode compartment of the electrochemical cells. One blower is used for each process loop. The process air flows in parallel through the 48 cells of each group of three modules. The blowers are located downstream of the electrochemical modules such that heat generated by the blowers will not have an adverse effect on the moisture balance within the electrochemical cells. The blower power used to control the cathode air flow rate is dissipated as heat into the cathode air stream exhausting the blower.

Cooling Air Blowers

The CS-6 contains two vane axial blowers to draw process air from the plenum over the fins of the electrochemical modules. Each blower draws the air in parallel over the fins of the 48 cells of a group of three modules. All heat dissipated as inefficiencies within the electrochemical module that is not removed by the cathode process air stream and process H_2 streams is removed by the cooling air stream. One cooling air blower is used for each process loop. The cooling air blowers are located downstream of the electrochemical modules. The amount of cooling air required is determined by the temperature differential between the dew point of the incoming process air and the dry bulb temperature of the exiting process air stream from the module. The cooling air blower speed is continuously modulated to vary the cooling air flow rate over the cell cooling fins as required. All power used by the cooling air blowers is dissipated as heat into the cooling air exiting the blowers.

Hydrogen Flow Sensor and Distribution Mounting

The CS-6 contains two H_2 flow sensor and distribution mountings designed to provide equal H_2 flow to each of the six CS-6 submodules. Each flow distribution block is located upstream of the three electrochemical modules it serves. The distribution block consists of three calibrated orifices and three flow sensors. Power required by the flow sensors is accounted for in the controllers and there is no heat generation. The blocks do affect H_2 stream pressure drop.

Primary Controller

The primary controller controls module current, process (cathode) air flow rate, and the process air inlet dew point to module temperature differential. Two control modes can be selected, Mode A and Mode B. In Control Mode A, current and process air flow rate are controlled at a constant level throughout CS-6 operation. In Control Mode B, both parameters are a function of an external 0 to 5 volt DC signal which is assumed to originate from a pCO_2 sensor. The module temperature control is independent of Control Mode A or B and basically is a control of the cooling air blower speed to maintain the process air inlet dew point to module temperature differential constant. The primary controller also sequentially actuates subsystem components to place them in the proper configuration as dictated by an operating mode command or when an out-of-tolerance condition is sensed by the primary controller. Primary controller-initiated shutdowns are those that are time critical and require immediate action. There are four primary controller initiated shutdowns: (1) high H_2 pressure (48 kN/m^2 (7.0 psig)), (2) low H_2 pressure ($<17 \text{ kN/m}^2$ (2.5 psig)), (3) high H_2 -in-air mixture ($>1.5\%$) in the front of the subsystem, and (4) high H_2 -in-air mixture ($>1.5\%$) in the back of the subsystem.

Power required to run the controllers, not including the electrochemical power generated by the electrochemical reactions, is dissipated as heat to the surrounding environment and not to any process stream.

Emergency Controller

The emergency controller consists of a shutdown sequencer to provide for proper component sequencing during an emergency controller-initiated subsystem shutdown. Any out-of-tolerance condition for any one of eight subsystem parameters can initiate this shutdown sequence. Those conditions which can cause a shutdown are:

1. High or low module temperature to inlet air dew point temperature differential (12.2K (22F)) above the inlet dew point air temperature or less than 8.9K (16F) above the inlet dew point temperature.
2. High power transistor temperature in the load transistor mounting heat sink assembly (in excess of 366K (200F)).
3. Greater than 2% H_2 -in-air mixture sensed by a combustible gas sensor located in the front of the subsystem.
4. Greater than 2% H_2 -in-air mixture sensed by a combustible gas sensor located in the rear of the subsystem.
5. High anode gas exhaust pressure in excess of 52 kN/m^2 (7.5 psig).
6. Loss of primary controller power.
7. A H_2 exhaust pressure less than 14 kN/m^2 (2.0 psig).

8. Low cell voltage in any one of the 96 cells (less than $-0.25V$).

Power utilized by the emergency controller is dissipated as heat given off to the surrounding cabin environment.

Load Transistor Mounting

The load transistor mounting is located in the outlet portion of the process air plenum to dissipate the power generated by the electrochemical cell reactions as heat and reject it to the process air stream leaving the plenum.

CS-6 MATH MODEL TEST PROGRAM

Experimentation specifically aimed at supporting the development of the CS-6 computer simulation model was required to establish the performance characteristics of the CS-6 and its individual LRUs. Seven tests were conducted. Six were directly used to characterize the performance of LRUs while the seventh established subsystem performance and intercomponent interface parameters for eventual math model computer program verification. The six LRUs characterized were: (1) the electrochemical modules (to compare predictability of the module math model previously developed), (2) the process air blowers, (3) the cooling air blowers, (4) the H_2 flow sensor and distribution mounting, (5) the primary controller, and (6) the emergency controller. The remaining LRUs consisting of valves and sensors were not characterized since valve power and heat loads are negligible and sensor power and heat load are included under either the primary or emergency controller.

Electrochemical Modules

A series of three experiments were conducted to verify the predictability of the electrochemical modules' performance within the CS-6 to determine if any upgrading of the previously established EDC cell math model was required. The electrochemical modules were characterized as a function of inlet pCO_2 , current density, and air flow rate over nominal operating ranges.

Process Air Inlet pCO_2

Module performance, specifically CO_2 removal efficiency, was experimentally characterized for a process air inlet pCO_2 range of 67 to 800 N/m^2 (0.5 to 6.0 mm Hg). The results of the pCO_2 test and the math model prediction curve for the test parameters are presented in Figure 5. The correlation between math model prediction and experimental data was excellent, thereby verifying the predictability of the electrochemical math model as a function of process air inlet pCO_2 .

Current Density

The effect of current density on electrochemical module performance was characterized for 10.8 to 37.7 mA/cm^2 (10 to 35 ASF). The results of the experiment and the math model prediction curve for the test parameters are presented in Figure 6.

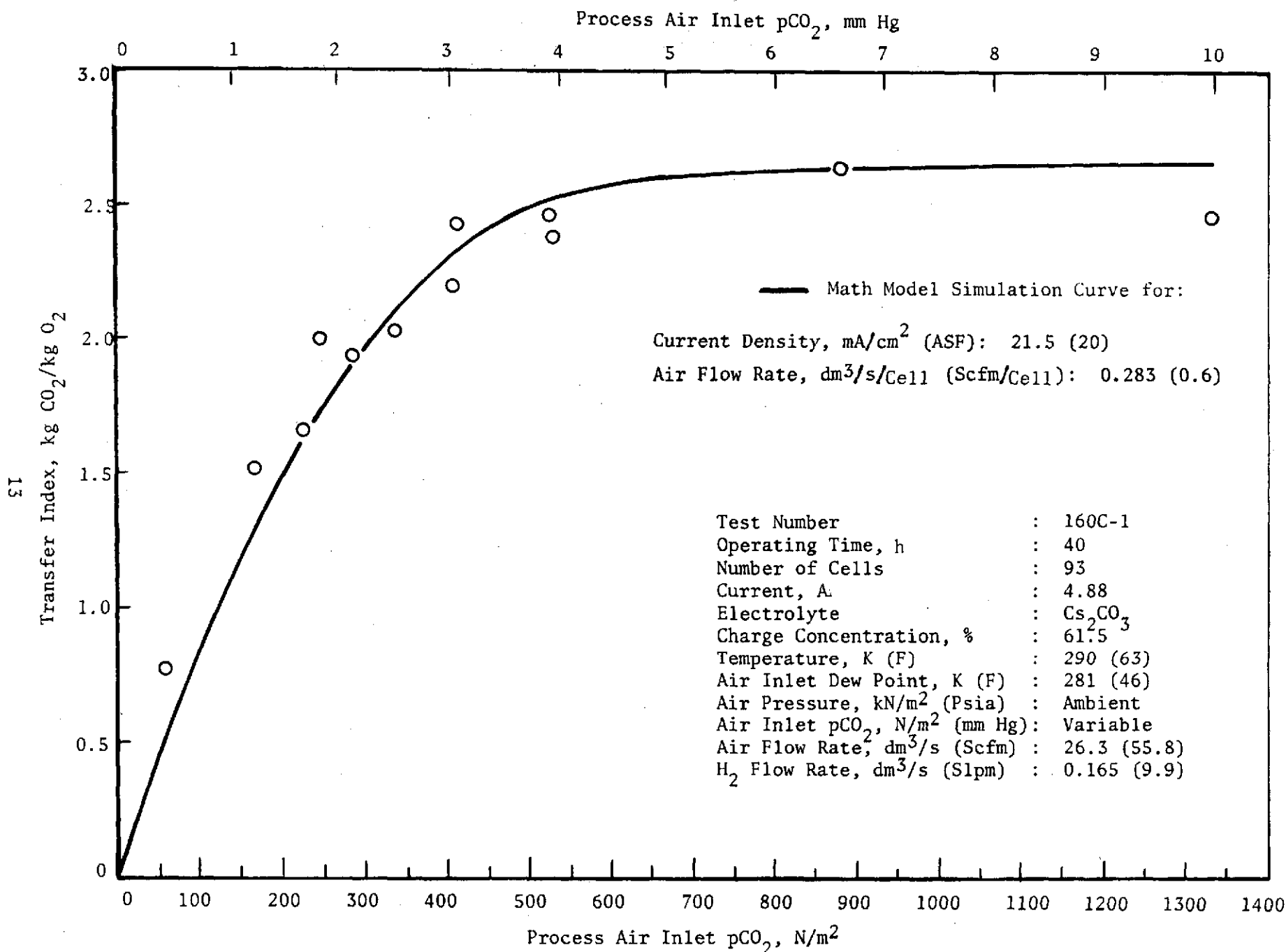


FIGURE 5 COMPARISON OF CS-6 PERFORMANCE DATA AND MATH MODEL
SIMULATION CURVE FOR TRANSFER INDEX VERSUS INLET $p\text{CO}_2$

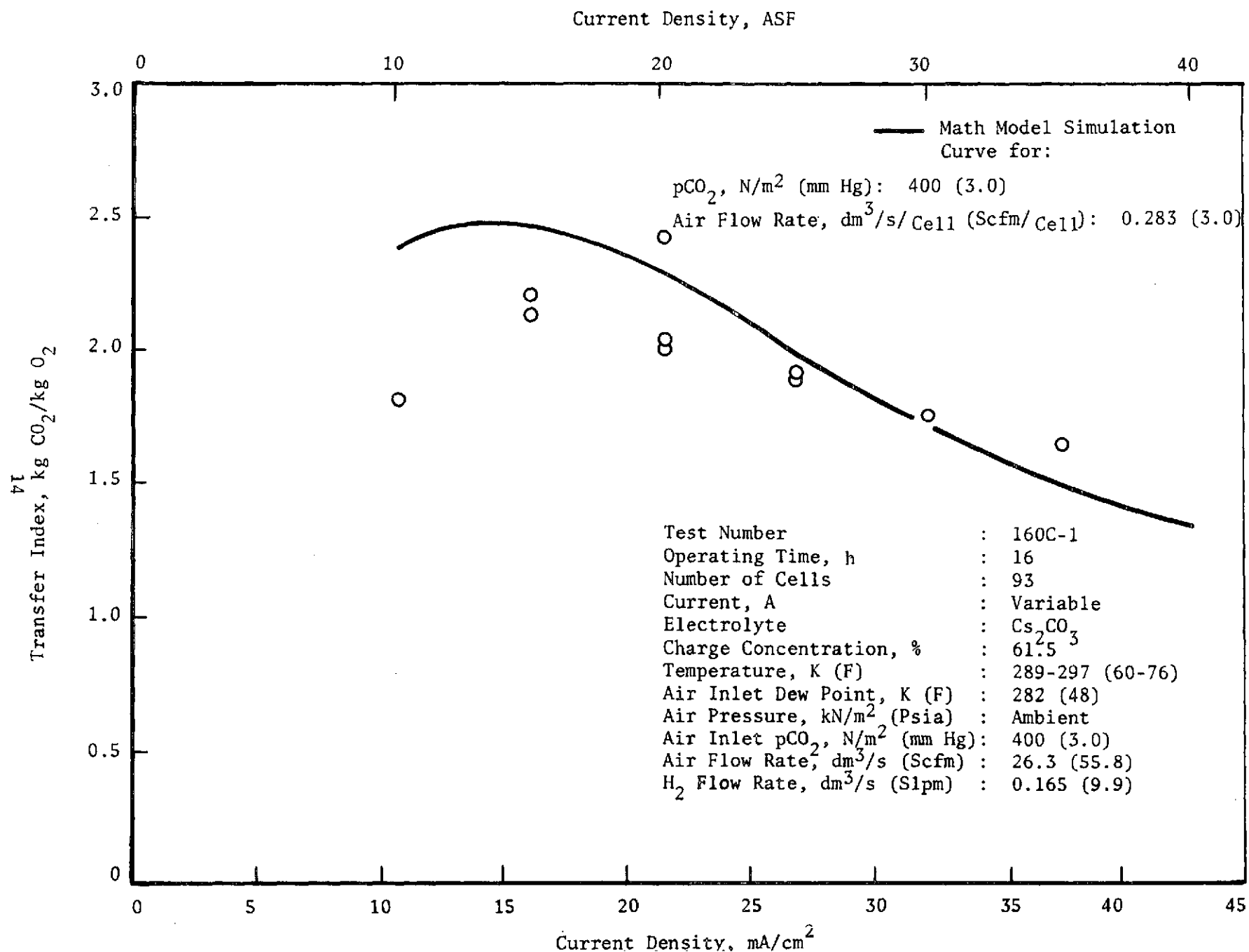


FIGURE 6 COMPARISON OF CS-6 PERFORMANCE DATA AND MATH MODEL SIMULATION CURVES FOR TRANSFER INDEX VERSUS CURRENT DENSITY

The test was conducted at CS-6 baseline interface conditions. At steady-state, moisture-in-balance conditions, the predictions of the math model as previously developed for CO₂ removal efficiencies agreed well with the performance data observed for the CS-6. At the lower current densities, the EDC cell math model predicted out-of-tolerance moisture conditions (wet) due to insufficient module heat generation (module subcooling). Subsystem operation at the lower current densities yielded lower than predicted transfer efficiencies characteristic of operation at wet conditions⁽⁵⁾. The data indicated excessively moist conditions, as correctly predicted by the math model. At the higher current densities, the math model predicted that the cell moisture conditions were removing water from the electrolyte causing the modules to dry out. Subsystem operation at the higher current densities yielded higher than predicted CO₂ removal efficiencies characteristic of operation at dry conditions⁽⁵⁾. The data indicated very dry moisture conditions within the modules, as correctly predicted by the math model. The deviations from in-moisture-balance operation were caused by the variation in cell current density which changes the amount of water and waste heat generated while maintaining the air flow rate and process air inlet moisture conditions constant at SSP baseline conditions without adjustment in module temperature level.

The previously established EDC cell math model predicts CO₂ removal efficiencies based on the assumption that the cells are operating at steady-state conditions and that moisture balance is maintained within a specific, optimum range. Steady-state operation, however, can also be achieved at less than optimum moisture conditions within the electrochemical modules. Since this latter condition is a possible operating mode for the CS-6, a moisture balance correction to allow prediction of CO₂ removal efficiencies as a function of the cell moisture conditions, as indicated by the data, was subsequently incorporated prior to completing the CS-6 subsystem math model.

Cathode Air Flow Rate

The effect of varying cathode air flow rates was characterized for the range of 14.2 to 28.3 dm³/s (30 to 60 scfm). The results of the experiment and the EDC cell math model prediction curve for the test parameters are presented in Figure 7.

Air flow rate has a large effect on the heat and water removal rates and the moisture balance conditions within the electrochemical cells. The data used in the CO₂ removal efficiency correlation of the EDC cell math model was, as stated above, based on cells operating in an optimum moisture balance range and did not take into account the large changes in cell moisture conditions caused by varying the air flow rate, as experienced in the actual subsystem operation. The CO₂ removal efficiency correlation of the initial EDC cell math model was, therefore, not adequate to predict CO₂ removal efficiency as a function of air flow rate. Subsequently, additional data gathered on the CS-6 after the completion of the original EDC cell math model was used to upgrade the air flow correlation for electrochemical modules. This upgraded version was included in the CS-6 Base Program.

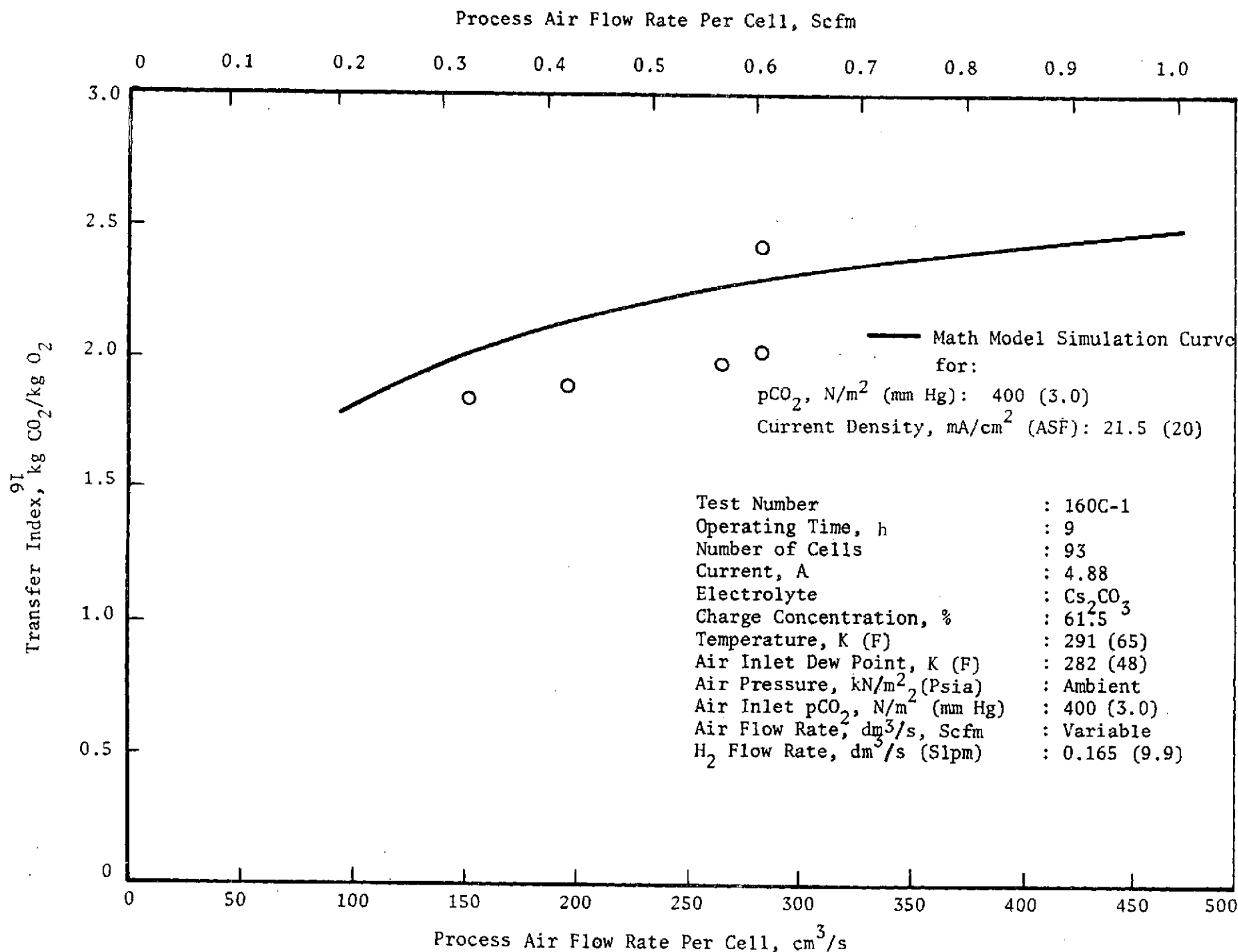


FIGURE 7 COMPARISON OF CS-6 PERFORMANCE DATA AND MATH MODEL SIMULATION CURVES FOR TRANSFER INDEX VERSUS AIR FLOW RATE

Process Air Blowers

The two CS-6 process air blowers were characterized to obtain air stream pressure drops and blower power and heat load as a function of process (cathode) air flow rate. The major pressure drop producing components in this air stream are the EDC modules. The results of the module pressure drop versus flow rate experiment are shown in Figure 8. System pressure drop as a function of air flow rate is given in Figure 9. Blower power for the process air blower of Section 1 and Section 2 as a function of air flow rate, at a corresponding system pressure drop, is given in Figures 10 and 11, respectively.

The modules and system pressure drop versus air flow rate curves relate typical pressure drop data as a function of air flow rate. The blower power curve, however, contains a spike at 14.2 to 16.5 cm^3/s (30 to 35 scfm), resulting from the combination of blower motor characteristics and blower speed control circuitry. The spike was verified during all forms of operation and implies that only a small change in air flow rate at flow rates greater than 14.2 dm^3/s (30 scfm) can cause large variations in the blower power requirement.

Cooling Air Blowers

The two CS-6 cooling air blowers were experimentally characterized to establish blower power, heat load, and cooling air passage pressure drop. The results of the cooling air pressure drop versus air flow rate test at two levels of plenum inlet pressure levels are presented in Figure 12. The pressure drop associated with ducting to and from the electrochemical modules did not significantly contribute to the cooling air pressure drop in comparison to the module cooling air pressure drop. The cooling air blower power versus air flow rate curves are shown in Figure 13.

Figure 13 shows that for a plenum inlet air pressure of 286 to 336 N/m^2 (1.15-1.35 in water), a certain amount of cooling air (approximately 10 dm^3/s (21 cfm) flows through the cooling air passages with the cooling blowers off, i.e., blower power equal to zero. The amount of air that bypasses the plenum and flows over the cooling fins of the modules, when the cooling air blowers are off, is determined by the overall system process air flow rate entering the plenum. The higher the total system process air flow the higher the plenum pressure differential and the higher the leakage air flow through the cooling air passages. Dampers were installed in the cooling air passages to prevent this bypass flow from occurring during times when cooling is not required. The dampers, however, were not totally leak-tight and some air flow constantly bypassed through the cooling air passages during cooling blower off operation. This contributed to module subcooling during low current density and high process (cathode) air flow rates.

Primary Controller

The CS-6 primary controller was characterized to determine the heat load and the power required during steady-state CS-6 operation. All blower power, which only passes through the controller, is handled separately and is not included in this

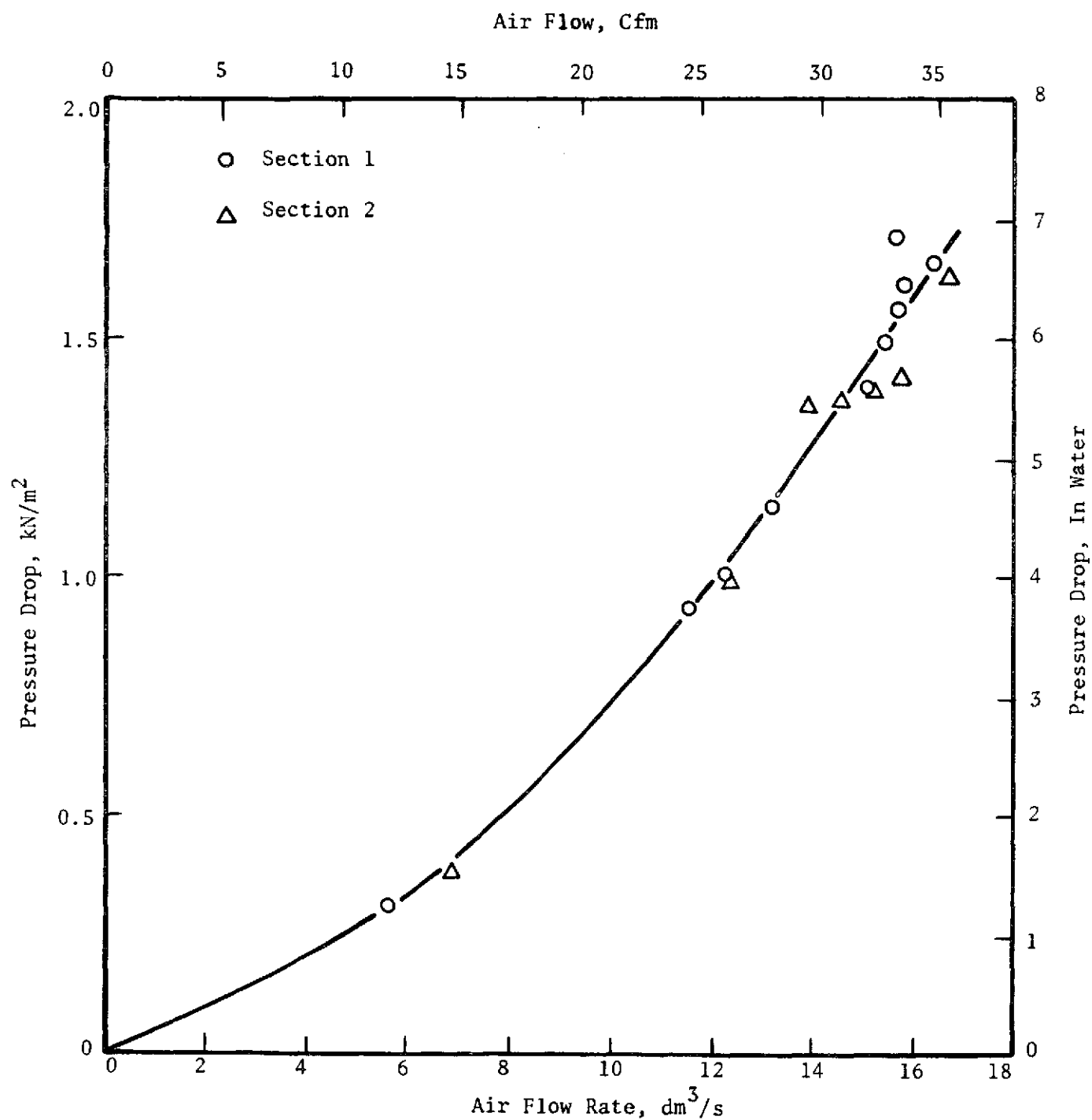


FIGURE 8 EDC MODULE PROCESS AIR PRESSURE DROP
VERSUS AIR FLOW RATE

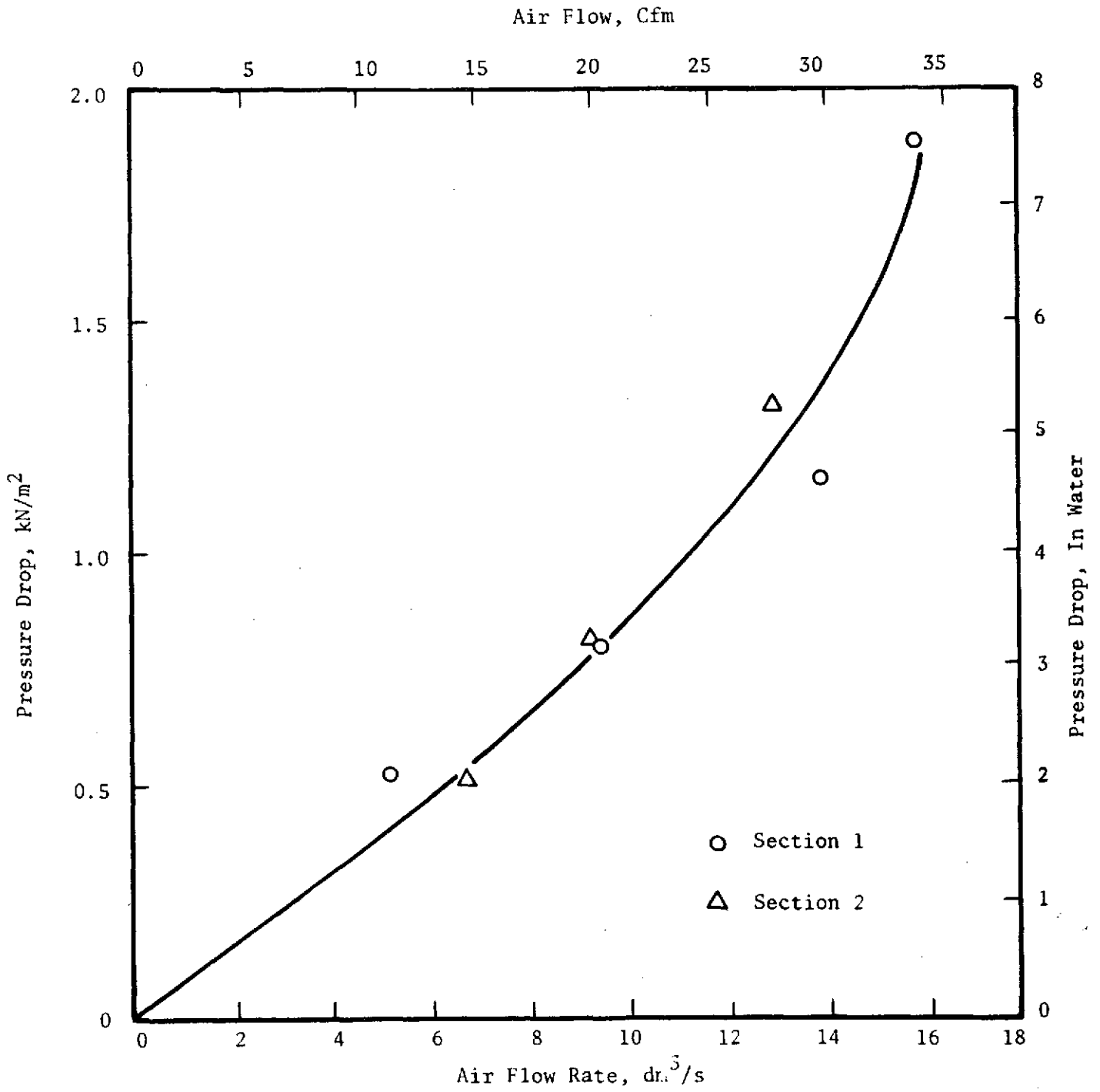


FIGURE 9 SYSTEM PROCESS AIR PRESSURE DROP VERSUS AIR FLOW RATE

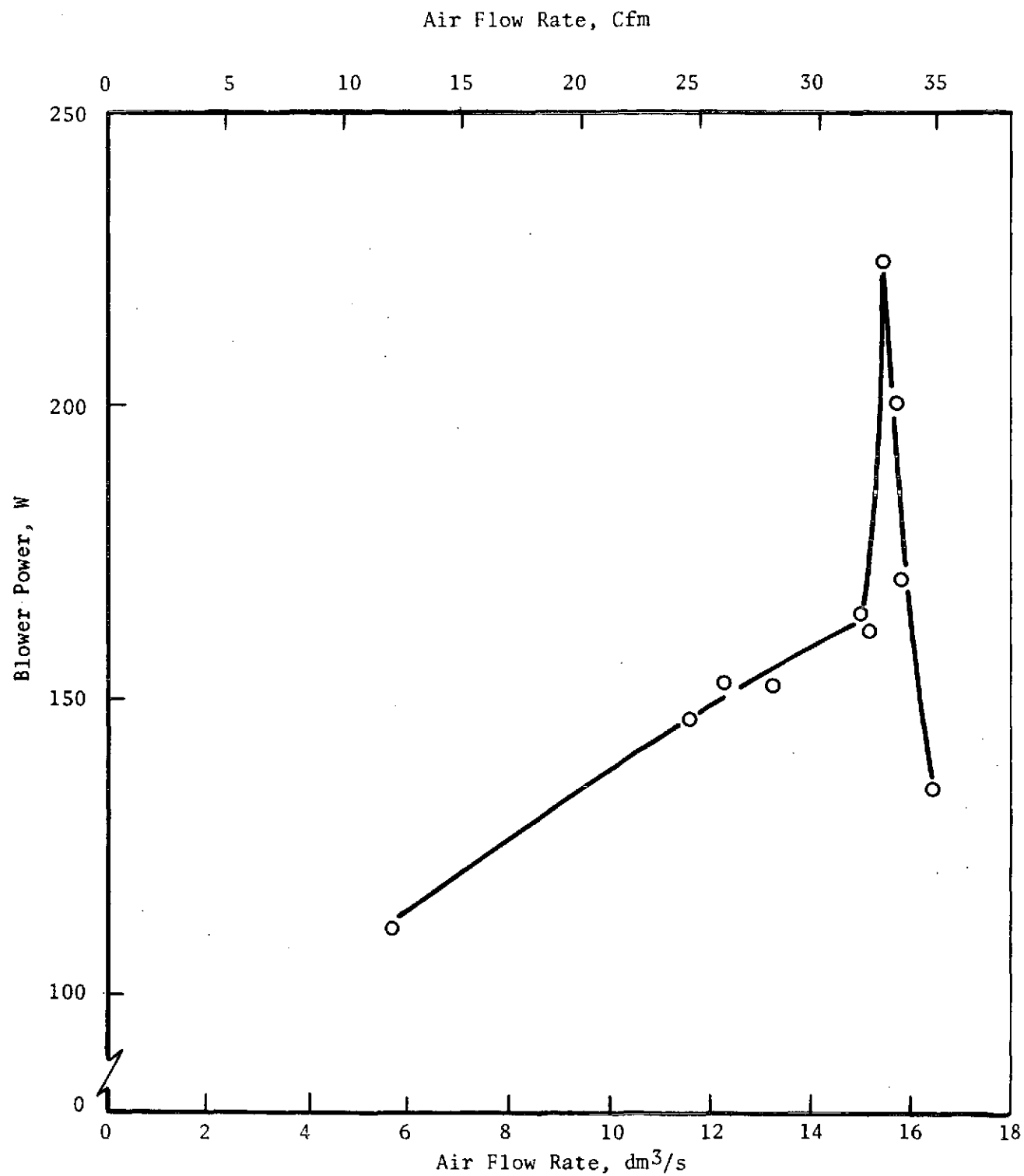


FIGURE 10 PROCESS AIR BLOWER POWER VERSUS AIR FLOW RATE
(SECTION 1)

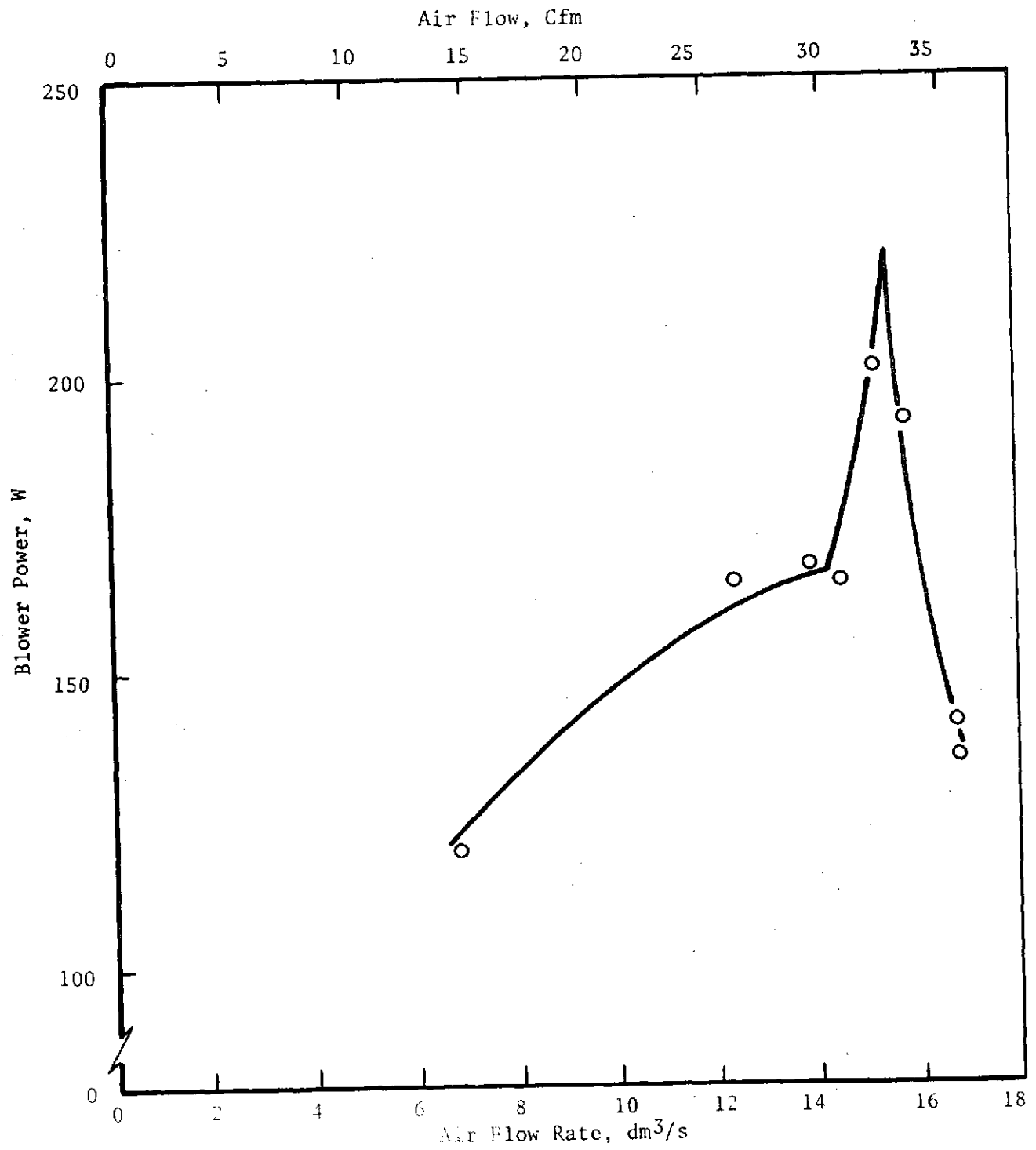


FIGURE 11 PROCESS AIR BLOWER POWER VERSUS AIR FLOW RATE
(SECTION 2)

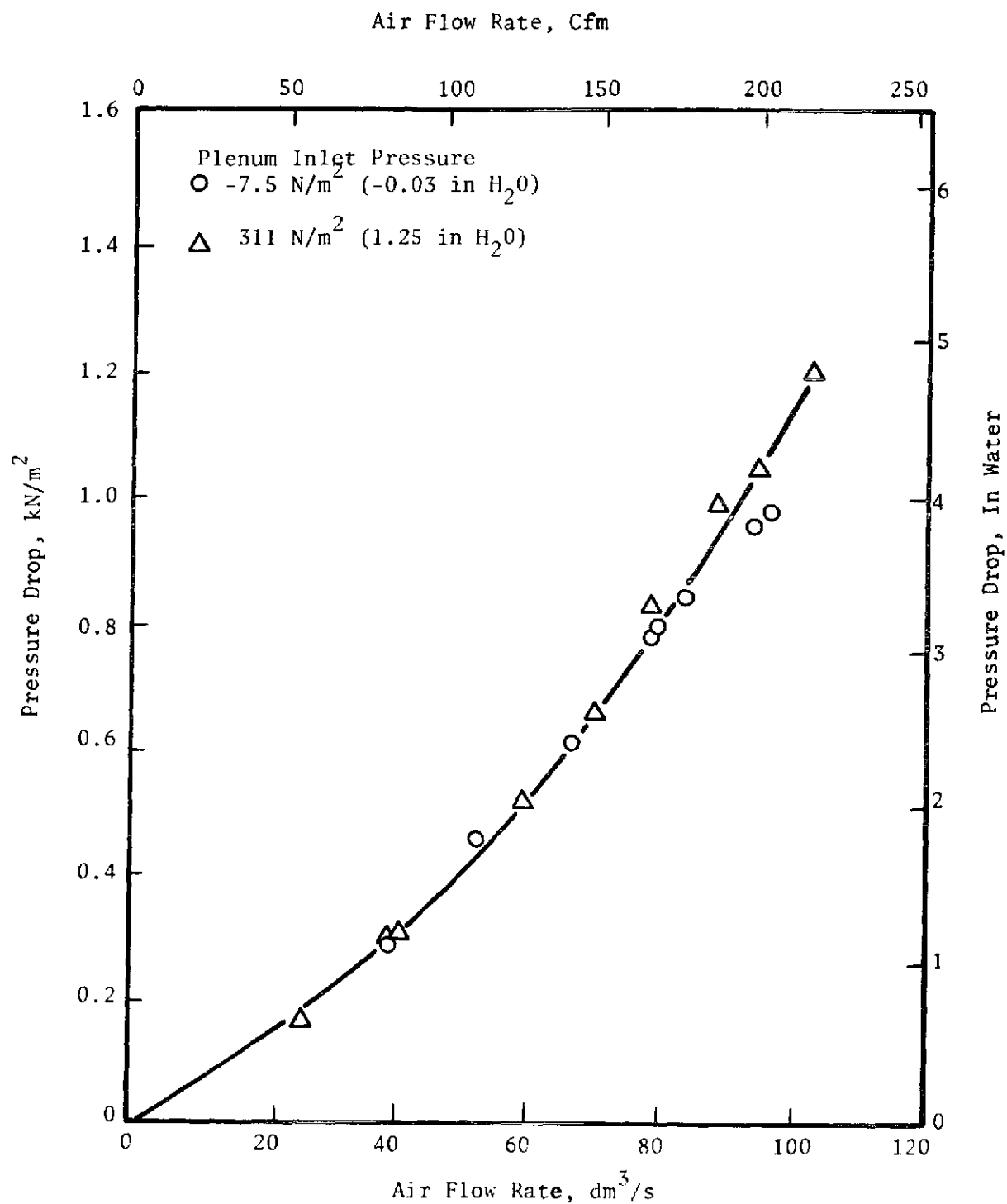


FIGURE 12 COOLING AIR PRESSURE DROP VERSUS AIR FLOW RATE

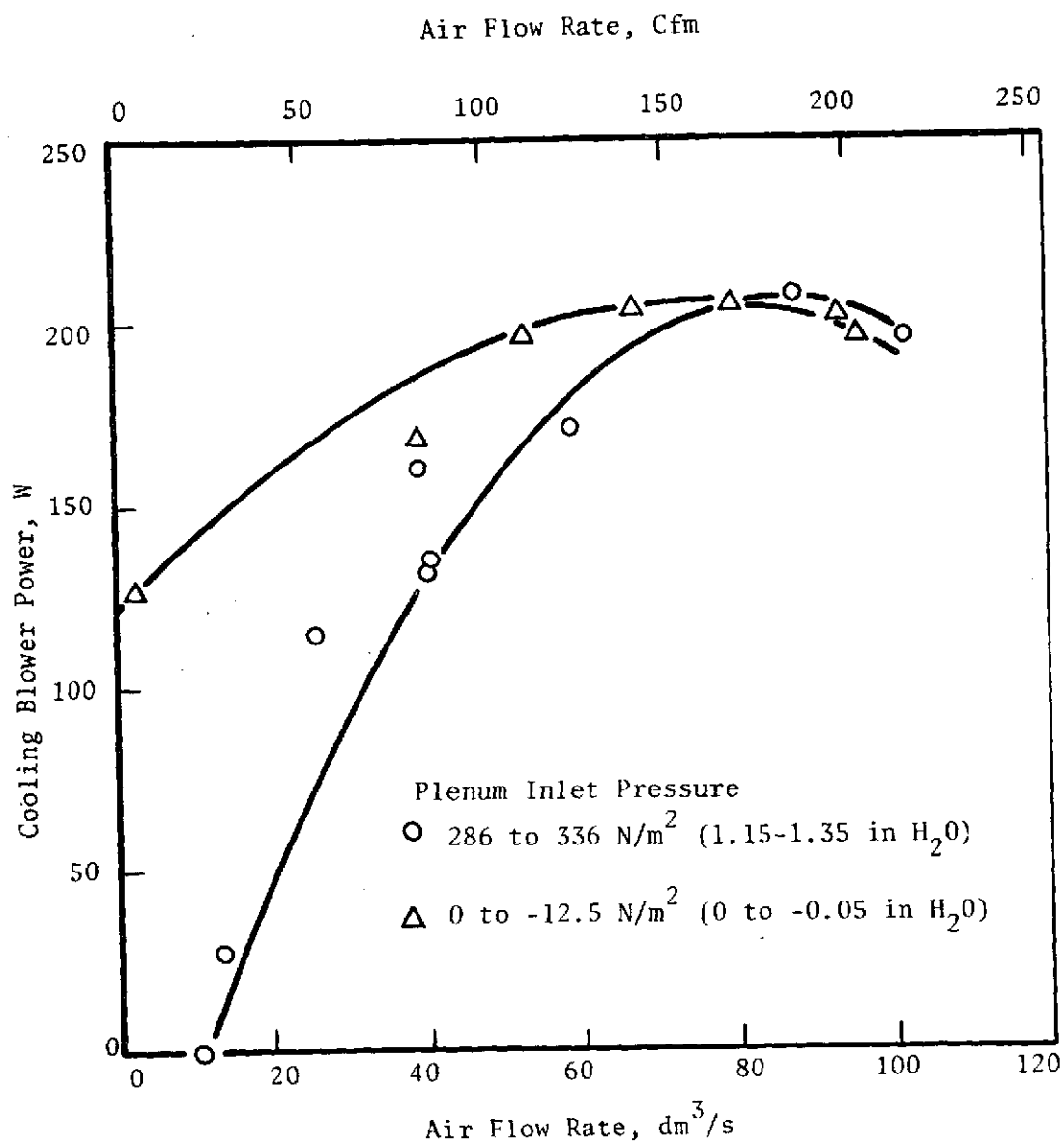


FIGURE 13 COOLING AIR BLOWER POWER VERSUS AIR FLOW RATE

requirement. The amount of power attributed to the primary controller to control the operation of the CS-6 subsystem at steady-state conditions as measured by a wattmeter on the power input was 85 watts. This power requirement is constant and independent of subsystem parameter variations (i.e., current density, cooling blower speed, or process air blower speed).

Emergency Controller

The CS-6 emergency controller was characterized to obtain the heat load and the power required during steady-state operation. The steady-state emergency controller power, as measured by a wattmeter, was 45 watts during normal CS-6 operation. This power requirement is constant and independent of subsystem parameter variations.

CS-6 Subsystem

The CS-6 subsystem was characterized as a function of process air inlet $p\text{CO}_2$, current density, and process air flow rate to determine intercomponent interface conditions between LRUs within the CS-6. The objective of the testing was to verify CS-6 math model prediction using these various intercomponent temperatures, pressures, etc. The testing consisted of running the CS-6 at steady-state conditions and monitoring pressures and temperatures throughout the system as a function of changes in inlet $p\text{CO}_2$, cell current density, and process air flow rate. The location of the sampling taps are shown in Figure 14. The results of the tests are presented in Table 3 and were used to verify math model prediction. The subsystem was tested using existing ground support test equipment which was not capable of supplying the total process air requirement to the plenum inlet. Only cooling air was supplied to the plenum. Process air was supplied to the electrochemical modules by a separate Air Supply Unit (ASU) at the required $p\text{CO}_2$, dew point, and dry bulb temperature. The cooling air stream was at ambient $p\text{CO}_2$ levels, but the temperature and dew point were maintained close to that of the process air from the ASU. Exact temperature and dew point correlation, however, was not obtained. Table 3 represents the data as if the CS-6 had been run in its designed configuration (i.e., all process air entering the plenum). Slight discrepancies in stream temperatures and dew points are present, but they had no affect on the modeling effort.

Hydrogen Flow Sensor and Distribution Mounting

The two H_2 flow sensor and distribution mounting blocks were characterized to obtain the nitrogen (N_2) and H_2 pressure drops as a function of flow rate through the distribution mounting. The results of the N_2 and H_2 pressure drop experiments are given in Figure 15. The H_2 pressure drop through the EDC modules was also characterized and is presented in Figure 16.

CS-6 BASE PROGRAM

The CS-6 Base Program is the computer program that was written to simulate the steady-state performance of the CS-6 as a function of variations in inlet stream composition temperatures and flow rates, outlet stream pressures, and the CS-6

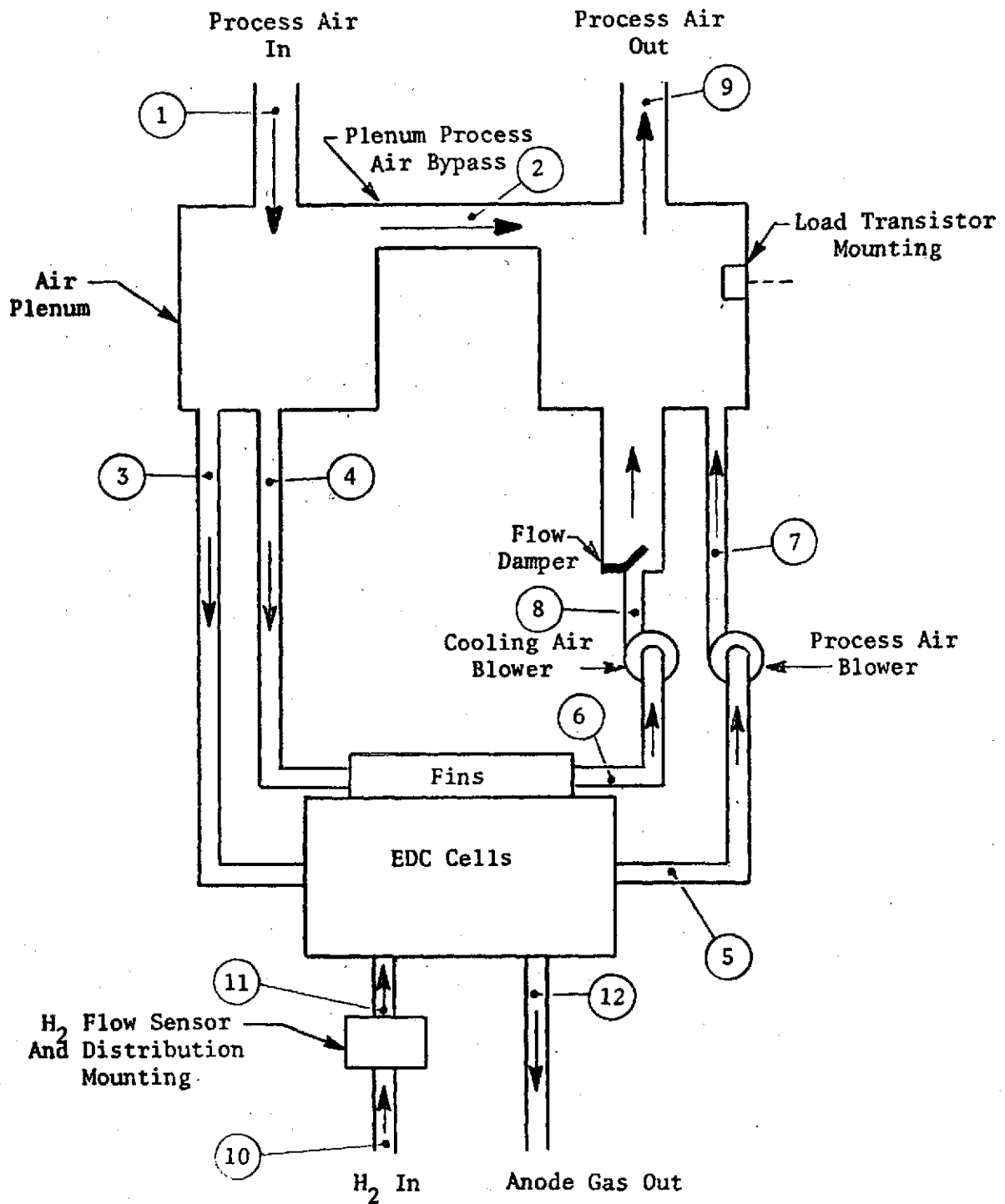


FIGURE 14 LOCATION OF GAS SAMPLING PORTS

TABLE 3 CS-6 INTERCOMPONENT INTERFACE PARAMETERS FOR
BASELINE OPERATING CONDITIONS^(a)

	1	2	3	4	5	6	7	8	9	10	11	12
Flow Rate, dm ³ /s	210	165	25	19	25	19	25	19	210	0.162	0.162	0.154
Scfm	444	350	54	40	54	40	54	40	444	-	-	-
Slpm	-	-	-	-	-	-	-	-	-	9.7	9.7	9.25
Pressure, ^(b) kN/m ²	0.242	0.075	-0.580	X ^(c)	1.910	0.030	0.062	X	0.060	51.3	34.6	X
In H ₂ O	0.97	0.30	-2.33	X	-7.67	0.12	0.25	X	0.24	-	-	-
Psig	-	-	-	-	-	-	-	-	-	7.4	5.0	X
Temperature, K	284	284	286	284	291	290	299	X	284	297	297	291
F	51.5	51.5	55.8	51.5	64.8	63.0	78.5	X	51.8	76.0	76.0	65.0
Dew Point, K	277	277	282	277	284	277	284	277	279	296	296	286
F	40.0	40.0	48.0	40.0	51.2	40.0	51.2	40.0	43.2	74.0	74.0	56.0

(a) Cell current = 4.88A.

(b) Above ambient.

(c) X indicates data not taken.

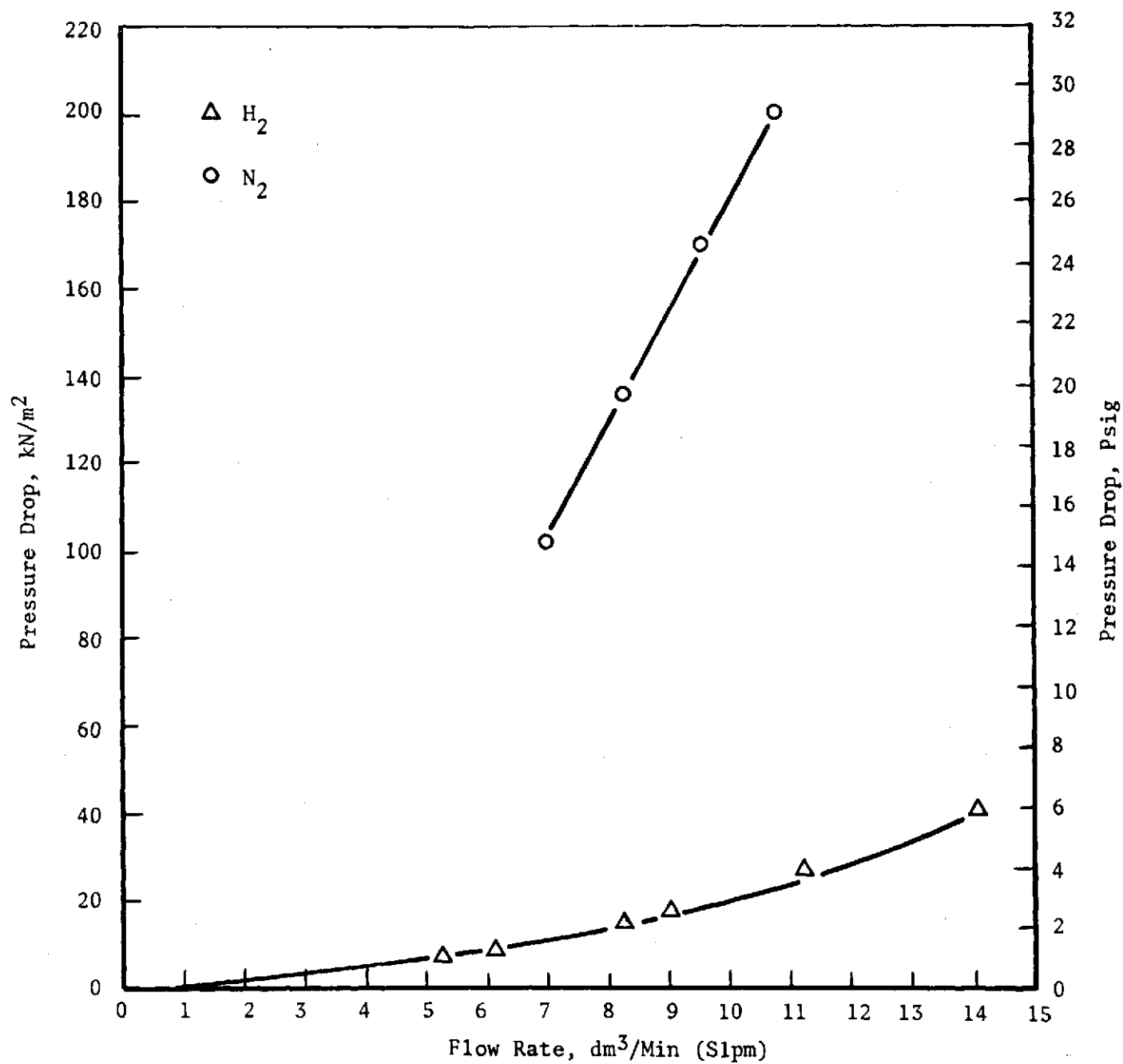


FIGURE 15 H₂ DISTRIBUTION BLOCK PRESSURE DROP
FOR PROCESS H₂ AND N₂ PURGE

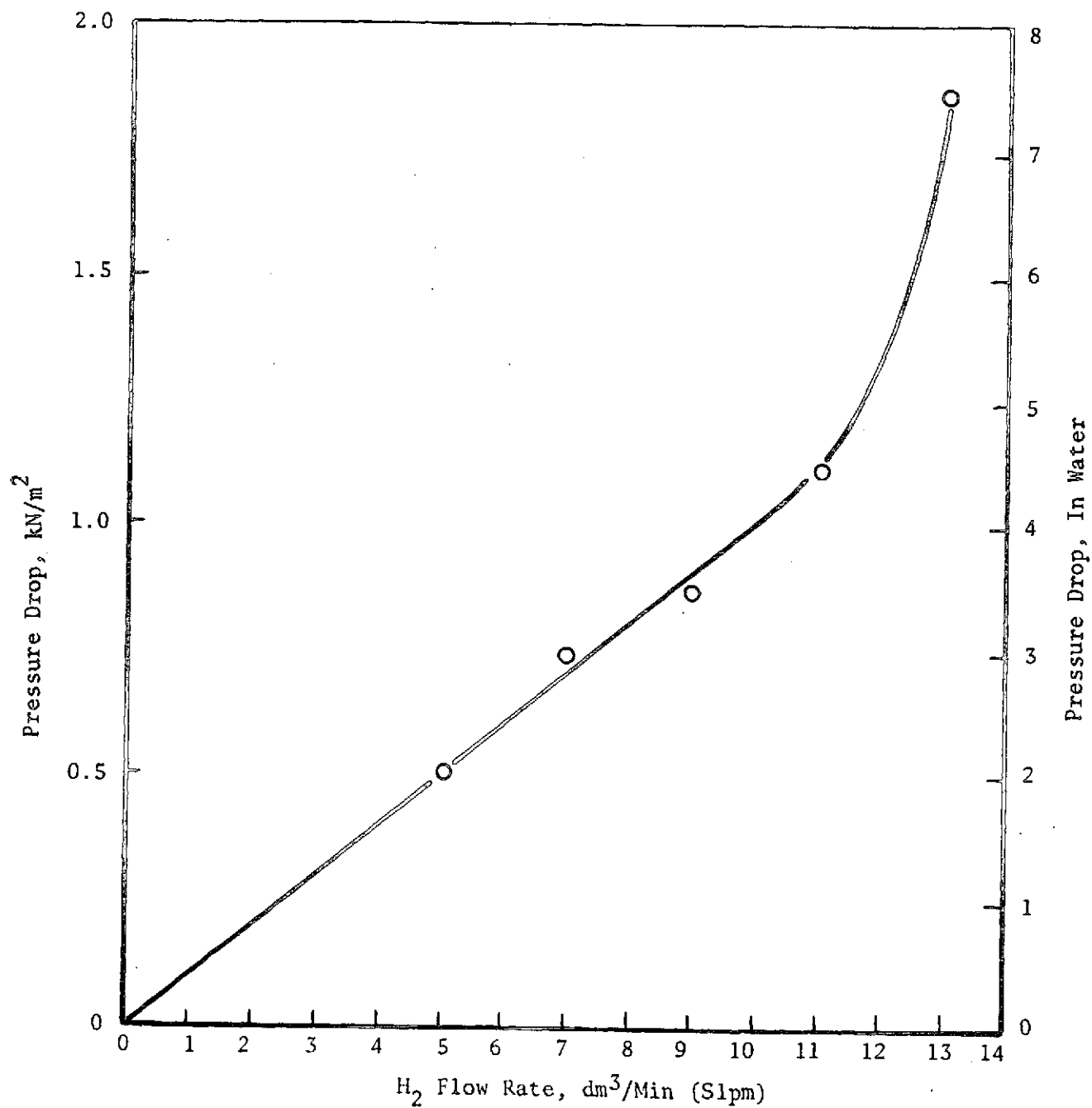


FIGURE 16 H₂ PRESSURE DROP ACROSS MODULES

control parameters. The CS-6 input variable ranges are given in Table 4. All inputs to the computer program are entered in the engineering units shown in Table 4. Table 5 is a complete list of the program input and output variables and their units. The program also provides various checks to insure that input data is within the model's range of predictability and to identify out-of-tolerance operating conditions.

The program contains previously developed correlations describing the performance of the EDC cells.⁽¹⁾ Additional correlations were developed describing CS-6 subsystem LRUs and process streams. The Base Program combines these correlations with steady-state mass and energy balances, and the program checks to simulate steady-state CS-6 performance. The original EDC math model computer program was not used directly as a subroutine in the Base Program since the assumption of cooling air being delivered at the required rate, optimum moisture balance conditions, and exact control of module temperature were not applicable because of the characteristics of the subsystem hardware. A certain amount of program rearranging was also desired to decrease computer running time by calculating those items that require an iterative solution prior to the gross calculation of stream variables.

Model Analyses

The math model which resulted in the CS-6 Base Program was developed by first defining the inlet and outlet stream characteristics and parameters for the CS-6 at the subsystem level. An initial computer program was written to describe the subsystem interfaces by expanding the math model developed for the EDC cells. The analyses that were used to derive the mathematical expressions describing the CS-6 intercomponent interface parameters were developed and incorporated into the initial program as required to calculate the remaining program outputs.

To clarify variable notation, numerical identifiers were given to the process streams and equation variables. The stream identification numbers are presented in Figure 17.

Process Air Correlations

The inlet process air stream to the CS-6 is divided into three streams: the cooling air stream, the process (cathode) air stream, and the air plenum bypass stream. Mathematical expressions were required and developed to describe the stream flow characteristics and blower power requirements.

Cooling Air Pressure Drop. The pressure drop associated with flow through the cooling air passages is the same as the pressure drop measured across the cooling air fins of the electrochemical modules since the pressure drop associated with the ducting is negligible. The correlation describing the cooling air passage pressure drop was derived by a least squares curve fit of pressure drop data as a function of air flow rate to a general quadratic equation. The equation was forced to pass through the origin so that there would be zero pressure

TABLE 4 CS-6 BASE PROGRAM INPUT VARIABLE RANGES

Cabin Atmosphere		
Total Pressure, PØPSA		13.7-15.7 Psia
pCO ₂ , PCØ		0.5-10 mm Hg
pO ₂ , POØPSA		2-4 Psia
Process Air Outlet		
Total Pressure, P8PSA		13.7-15.7 Psia
Process Air Inlet		
Temperature, T7		44-80F
Flow Rate, V7		0-600 Scfm ^(a)
Dew Point Temperature, DW7		41-70F
Anode H ₂ /CO ₂ Outlet		
Total Pressure, P4PSA		14.8-21.2 Psia
System H ₂ Inlet		
Temperature, T9		65-75F
Flow Rate, V9SL		0-18 Scfm ^(a)
Dew Point Temperature, DW9		10-75F
Modules		
Number of Cells in Current, N		90-96
Current, I		2.44-9.76 A
DELT1 ^(b)		10-25F
Cathode Air Flow Rate, V1		19.2-76.8 Scfm (96 cells)
Penalty Weight Factors		
Power, PWPEN		0-2 Lb/Watt
Heat Rejection to Ambient, HTPEN		0-2 Lb/Btu/Hr
Water Vapor Rejection to Ambient, H2OPEN		0-500 Lb/Lb H ₂ O/Hr
Oxygen Consumption, OXPEN		0-3000 Lb/Lb O ₂ /Hr
Program Control		
NFLAG ^(c)		0-1

(a) Reference conditions for standard flow units: 70F, 14.7 Psia

(b) DELT1 = (Module temperature - cathode air inlet dew point temperature)

(c) NFLAG = 0 Out of tolerance moisture conditions do not stop program.

1 Out of tolerance moisture conditions do stop program.

TABLE 5 CS-6 BASE PROGRAM INPUT AND OUTPUT VARIABLES

Input Variables

Cabin Atmosphere	Total Pressure, Psia pCO ₂ , mm Hg pO ₂ , Psia
Process Air Outlet	Total Pressure, Psia
Process Air Inlet	Temperature, F Flow Rate, Scfm Dew Point Temperature, F
Anode H ₂ /CO ₂ Outlet	Total Pressure, Psia
Anode H ₂ Inlet	Temperature, F Flow Rate, Slpm Dew Point Temperature, F
Modules	Number of Cells in Circuit Current, A DELT1(a), F Cathode Air Flow Rate, Scfm
Penalty Weight Factors	Power Consumption, Lb/Watt Heat Rejection, Lb/Btu/Hr Water Vapor Rejection, Lb/Lb/Hr O ₂ Consumption, Lb/Lb/Hr
Control	NFLAG 0 = ignore out-of-tolerance moisture conditions 1 = abort for out-of-tolerance moisture conditions

Output Variables

Control	Preferred Value of DELT1(a), F
Module	Transfer Index, Lb CO ₂ /Lb O ₂ Transfer Efficiency, % Cell Voltage, V Module Voltage, V CO ₂ Removal Rate, Lb/Hr O ₂ Consumption Rate, Lb/Hr H ₂ Consumption Rate, Lb/Hr Water Production Rate, Lb/Hr Current Density, A/Ft ² Heat Load of Modules, Btu/Hr Power Production of Modules, Watt

(a) DELT1 = Module Temperature - Inlet Cathode Air Dew Point Temperature

-continued-

Table 5 - continued

Cathode Air Inlet

Total Pressure, mm Hg
 $p\text{CO}_2$, mm Hg
 $p\text{H}_2\text{O}$, mm Hg
 CO_2 Flow Rate, Lb/Hr
 Water Flow Rate, Lb/Hr
 CO_2 Flow Rate, Scfm
 Water Flow Rate, Scfm
 O_2 Flow Rate, Scfm
 N_2 Flow Rate, Scfm
 Temperature, F
 Dew Point Temperature, F
 Relative Humidity, %

Cathode Air Outlet

Total Pressure, mm Hg
 Module Cathode Air Pressure Drop, mm Hg
 $p\text{CO}_2$, mm Hg
 $p\text{H}_2\text{O}$, mm Hg
 Total Flow Rate, Scfm
 CO_2 Flow Rate, Scfm
 Water Flow Rate, Scfm
 O_2 Flow Rate, Scfm
 N_2 Flow Rate, Scfm
 CO_2 Flow Rate, Lb/Hr
 Water Flow Rate, Lb/Hr
 Temperature, F
 Dew Point Temperature, F
 Relative Humidity, %
 Cathode Air Blower Outlet Total Pressure, mm Hg
 Cathode Air Blower Outlet Flow Rate, Scfm
 Cathode Air Blower Outlet Temperature, F

Process Air Inlet

Total Pressure, mm Hg
 $p\text{H}_2\text{O}$, mm Hg
 $p\text{N}_2$, mm Hg
 CO_2 Flow Rate, Scfm
 Water Flow Rate, Scfm
 O_2 Flow Rate, Scfm
 N_2 Flow Rate, Scfm
 Dew Point Temperature, F
 Relative Humidity, %

Process Air Outlet

Total Pressure, mm Hg
 $p\text{CO}_2$, mm Hg
 Plenum Bypass Flow Rate, Scfm
 Plenum Bypass Pressure Drop, mm Hg
 Total Flow Rate, Scfm
 Water Flow Rate, Scfm
 CO_2 Flow Rate, Scfm

Table 5 - continued

Process Air Outlet	O_2 Flow Rate, Scfm pH_2O , mm Hg Temperature, F Dew Point Temperature, F Relative Humidity, %
H_2 Inlet	Total Pressure, mm Hg Water Vapor Pressure, mm Hg Distribution Block Pressure Drop, mm Hg Module Inlet Total Pressure, mm Hg Module Inlet pH_2O , mm Hg Module Inlet pH_2 , mm Hg Total Flow Rate, Scfm H_2 Flow Rate, Scfm Water Flow Rate, Scfm H_2 Flow Rate, Lb/Hr Minimum Required Flow Rate, Slpm
H_2 Outlet	Total Pressure, mm Hg Module Anode Gas Pressure Drop, mm Hg Water Vapor Pressure, mm Hg Flow Rate, Scfm CO_2 Flow Rate, Scfm H_2 Flow Rate, Scfm Water Flow Rate, Scfm Flow Rate, Slpm CO_2 Flow Rate, Slpm H_2 Flow Rate, Slpm Total Flow Rate, Lb/Hr CO_2 Flow Rate, Lb/Hr H_2 Flow Rate, Lb/Hr Water Flow Rate, Lb/Hr Dew Point Temperature, F CO_2 - H_2 Weight Ratio, Lb CO_2 /Lb H_2 H_2 - CO_2 Volume Ratio, Slpm H_2 /Slpm CO_2
Heat Balance, Modules	Modules Heat Load, Btu/Hr Cathode Air Heat Pickup, Btu/Hr Anode Gas Heat Pickup, Btu/Hr Cooling Air Heat Pickup, Btu/Hr
Cooling Air	Inlet Pressure, mm Hg Coolant Channel Pressure Drop, mm Hg Outlet Pressure, mm Hg Flow Rate, Scfm Inlet Temperature, F Outlet Temperature, F

Table 5 - continued

Cooling Air	Heat Transfer Coefficient, Btu/Hr/Ft ² /F
	Fin Efficiency, %
	Flow Rate Over Cells in Circuit, Scfm
	In Circuit Outlet Temperature, F
	Cooling Blower Outlet Pressure, mm Hg
	Cooling Blower Outlet Flow Rate, Scfm
	Cooling Blower Outlet Temperature, F
	Cooling Damper Pressure Drop, mm Hg
	Minimum Leakage Flow Rate, Scfm
Actual Volumetric Flow Rates	Modules Cathode Air Inlet, Cfm
	Modules Cathode Air Outlet, Cfm
	Modules H ₂ Inlet, Cfm
	Modules H ₂ -CO ₂ Outlet, Cfm
	Modules Cooling Air Inlet, Cfm
	Modules Cooling Air Outlet, Cfm
	Modules Cooling Air Outlet From Cells in Circuit, Cfm
	Process Air Inlet, Cfm
	Process Air Outlet, Cfm
	System H ₂ Inlet, Cfm
	Process Air Plenum Bypass Outlet, Cfm
	Cathode Air Blowers Outlet, Cfm
	Cooling Blowers Outlet, Cfm
	Cooling Dampers Outlet, Cfm
Equivalent Weight	Cooling Blower Power, Watt
	Cathode Blower Power, Watt
	Primary Controller Power, Watt
	Emergency Controller Power, Watt
	Data Acquisition Unit Power, Watt
	Total System Power, Watt
	Total Heat Rejection, Btu/Hr
	Power Consumption Penalty Weight, Lb
	Heat Rejection Penalty Weight, Lb
	Water Vapor Rejection Penalty Weight, Lb
	O ₂ Consumption Penalty Weight, Lb
	Hardware Weight, Lb
	Total Equivalent Weight, Lb

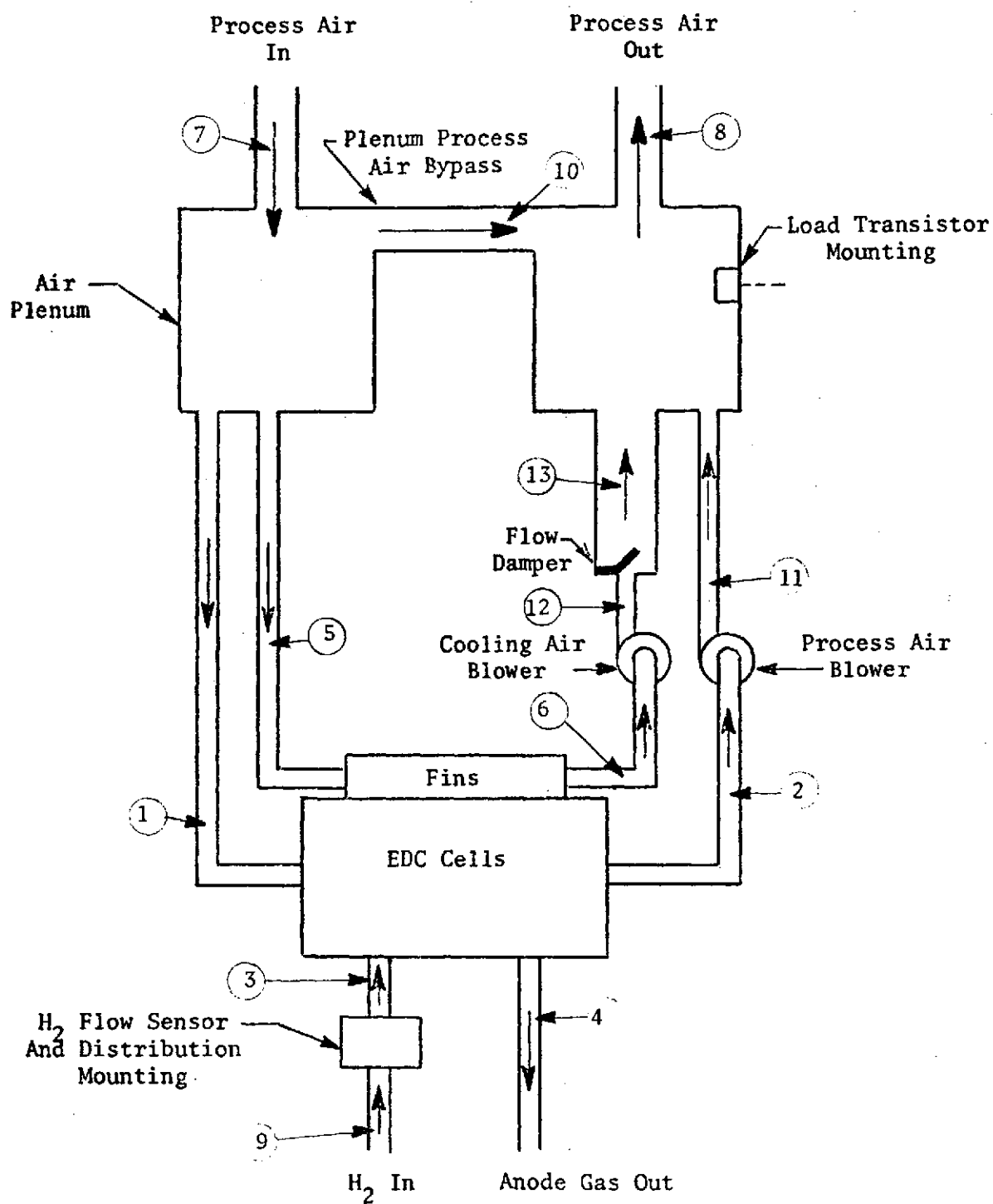


FIGURE 17 PROCESS STREAM IDENTIFICATION NUMBERS

drop at zero air flow rate. The correlation derived for the pressure drop as a function of cooling air flow rate was

$$\Delta P_{56} = 0.0101 V_5 + 1.303 \times 10^{-5} V_5^2 \text{ (a)} \quad (1)$$

where

ΔP_{56} = the cooling air pressure drop, mm Hg

V_5 = the cooling air flow rate, scfm

Plenum Bypass Pressure Drop. Air that is not drawn through the electrochemical modules or over the cooling fins bypasses the subsystem hardware through the air plenum bypass. A correlation describing the pressure drop as a function of the air plenum bypass flow rate was derived from experimental data. The experimental data was curve-fitted to a general equation describing the pressure drop as a function of the plenum bypass air flow rate squared. The mathematical expression obtained is

$$\Delta P_{78} = 2.25 \times 10^{-5} V_{10}^2 \quad (2)$$

where

ΔP_{78} = the air plenum bypass pressure drop, mm Hg

V_{10} = the air plenum bypass flow rate, scfm

The pressure drop was expressed as the square of the flow rate because of the high turbulent flow characteristics and the dominance of entrance and exit effects within the plenum bypass. The turbulence and entrance and exit effects both lead to a second power relationship^(6,7).

Cooling Air Damper Leakage Pressure Drop. Pressure drop associated with the cooling air dampers occurs when the cooling air blowers are off and cooling air leaks around the dampers. The geometry of the closed dampers is such that a slot flow correlation was indicated. The correlation derived from experimental data is

$$\Delta P_{1213} = 8.6117 \times 10^{-4} V_5^2 \quad (3)$$

where

ΔP_{1213} = the cooling air damper pressure drop, mm Hg

V_5 = the cooling air flow rate, scfm

The cooling air damper correlation presented only applies when the cooling air blowers are off. The dampers are weighted such that when the cooling air

(a) All variables used in the equation presented in the Model Analyses section use the common engineering units since the equations were derived for direct use in the computer program.

blowers start, the dampers open. The cooling damper leakage pressure drop is assumed to remain constant as the dampers open.

Flow Rate Through the Cooling Air Dampers. When the cooling air blowers are off, it is necessary to determine the cooling air flow rate caused by cooling air damper leakage. Air that is not drawn through the cathode compartments of the EDC cells must either flow through the cooling air dampers or the air plenum bypass during cooling air blower off operation. The air flow division is given by the equation

$$V7 = V10 + V5 + V1 \quad (4)$$

where

V7 = the inlet plenum air flow rate, scfm

V1 = the process (cathode) air flow rate, scfm

The pressure drop through the air plenum bypass and the cooling air dampers must be equal, and the air flow will therefore divide to obtain the equal pressure drops. The pressure drop equality is given by the equation

$$\Delta P78 = P56 + \Delta P1213 \quad (5)$$

The division of air flow rate between the air plenum bypass and the cooling air cavities can be calculated by solving equations (1-5) simultaneously for V5, given V1 and V7. The resulting equation is

$$V5 = \frac{-QB + [QB^2 - 4(QA)(QC)]^{\frac{1}{2}}}{2QA} \quad (6)$$

where

$$QA = -8.517 \times 10^{-4}$$

$$QB = (4.5 \times 10^{-5})(V7 - V1) + 0.0101$$

$$QC = -2.25 \times 10^{-5} (V7 - V1)^2$$

Substitution of V1, V7, and V5 into equations (2-5) yields V10, $\Delta P78$, $\Delta P56$, and $\Delta P1213$, respectively.

Process Air Inlet Pressure. The process air inlet pressure is calculated after the heat balance is done and all flow rates have been established through the three air passages. The inputs to the math model are the outlet pressure at the plenum as would be specified by the subsystem interfacing downstream of the CS-6. The process air inlet pressure then is equal to the outlet pressure plus the pressure drop across the plenum bypass, as given by the equation

$$P7 = P8 + \Delta P78 \quad (7)$$

where

P7 = the process air inlet pressure, mm Hg

P8 = the process air outlet pressure, mm Hg

EDC Module Pressure Drop. The expression for the process air drawn through the cathode compartment of the EDC cells was derived from experimental data. A general quadratic equation passing through the origin was least squares fit to the experimental data. The equation obtained is

$$\Delta P_{12} = 0.04877V_1 + 0.001903V_1^2 \quad (8)$$

where

ΔP_{12} = the EDC module pressure drop, mm Hg

Process Air Blower Power. The expression for the process air blower power as a function of air flow rate was derived from the experimental data gathered on both blowers. Because of the spike in the power curve caused by the blower speed controller, the total power curve was modeled by three straight line segments. The equations derived were

$$PWRCTB = 2.8V_1 + 153.8; \text{ for } V_1 \leq 62 \quad (9)$$

$$PWRCTB = 40V_1 - 2150; \text{ for } 62 < V_1 \leq 65 \quad (10)$$

$$PWRCTB = -34V_1 + 2660; \text{ for } 65 < V \leq 70 \quad (11)$$

where

PWRCTB = the process (cathode) air blower power, W

Cooling Air Blower Power. The cooling air blower power is a function of the cooling air flow rate and the air plenum bypass pressure drop. As air plenum bypass pressure drop increases (higher bypass flow rates), cooling air blower power was observed to decrease for a given cooling requirement. This decrease is caused by the increased leakage flow rate through the cooling air dampers at the higher plenum bypass pressure drop. Cooling blower power as a function of air flow rate was measured experimentally for two air plenum pressure drops. The correlations obtained through curve fitting for the two power curves are given by the equations

$$PWH = 410 - 0.00396 (V_5 - 368)^2 \quad (12)$$

$$PWL = 410 - 0.00178 (V_5 - 306)^2 \quad (13)$$

where

PWH = the power at ΔP_{78} of 1.25 in water, W

PWL = the power at ΔP_{78} of 0.05 in water, W

An empirically derived interpolation parameter, TR, is used to calculate the cooling air blower power at different plenum bypass pressure drops. The interpolation equation obtained was

$$\text{PWRCLB} = (\text{TR})(\text{PWH}) + (1-\text{TR})(\text{PWL}) \quad (14)$$

where

PWRCLB = the cooling blower power, W

$$\text{TR} = \left(\frac{\Delta\text{P78}}{2.4297} + 0.0385 \right)^A \quad (15)$$

$$A = 0.128 + 0.0546\Delta\text{P78} \quad (16)$$

Process Hydrogen Correlations

Correlations for the process H₂ stream were required to calculate the EDC module H₂ pressure drop as a function of H₂ flow rate, H₂ pressure drop across the H₂ flow and sensor distribution mounting, and to upgrade the anode gas outlet dew point correlation used in the EDC cell math model.

EDC Module Hydrogen Pressure Drop. The pressure drop through the anode compartment of the 16 series connected EDC cells as a function of H₂ flow rate was derived from experimental data. The two equations describing the anode compartment pressure drop are

$$\Delta\text{P34} = 0.3822 \left(\frac{14.1}{\text{P4}} \right)^{0.8} \text{ V3; for V3} < 22 \quad (17)$$

$$\Delta\text{P34} = \left(\frac{14.1}{\text{P4}} \right)^{0.8} [8.3183 + 0.4187 (\text{V3} - 21.5801)^{1.75}] \text{ for} \\ \text{V3} \geq 22 \quad (18)$$

where

ΔP34 = the anode pressure drop, mm Hg

V3 = the H₂ flow rate, slpm

P4 = the anode gas outlet pressure, psia

Hydrogen Distribution Mounting Pressure Drop. The pressure drop associated with H₂ flow through the H₂ distribution mounting was derived from experimental data. The two equations obtained are

$$\Delta\text{P93} = 10.64 \left(\frac{14.1}{\text{P3}} \right)^{0.8} \text{ V3; for V3} \leq 6.2 \quad (19)$$

$$\Delta P_{93} = \left(\frac{14.1}{P_3} \right)^{0.8} [35.14V_3 - 195.25 + e^{(7.75-0.6537V_3)}] ; \text{ for} \quad (20)$$
$$V_3 > 6.2$$

where

ΔP_{93} = the H_2 distribution mounting pressure drop, mm Hg

P_3 = module H_2 inlet pressure, psia

Anode Gas Dew Point Correlation. The anode gas dew point can be estimated from the module temperature and the inlet and outlet cathode air dew points. The correlation derived from experimental data is given by the equation

$$DW_4 = 0.77 \left(\frac{DW_1 + DW_2}{2} \right) + 0.23 (T_2) \quad (21)$$

where

DW_4 = anode gas outlet dew point, F

DW_1 = cathode air inlet dew point, F

DW_2 = cathode air outlet dew point, F

T_2 = module temperature, F

The data that was used to derive the correlation is presented in Table 6.

EDC Module Correlations

The EDC cell and module math model previously developed required upgrading in three areas: the module temperature and heat balance, the effect of process (cathode) air flow rate on CO_2 removal efficiency, and the effect of cell moisture conditions on CO_2 removal efficiency.

Module Temperature Correlation. The process (cathode) air out temperature, defined as the module temperature, is controlled to a set level above the process air inlet dew point temperature. The module temperature is maintained by controlling the cooling air blower speed to give the desired process air outlet to inlet air dew point temperature differential. Four conditions exist which prevent the module temperature control from maintaining the temperature differential:

1. Insufficient blower capacity.
2. Excessive cooling air damper leakage.
3. Insufficient cooling air temperature.
4. Insufficient module heat generation.

TABLE 6 ANODE GAS OUTLET DEW POINT TEMPERATURE CORRELATION DATA^(a)

Inlet Cathode Air Dew Point Temperature, K	280.9	281.4	280.3	281.4
Inlet Cathode Air Dew Point Temperature, F	46.0	47.0	45.0	47.0
Outlet Cathode Air Dew Point Temperature, K	284.2	284.0	283.8	284.3
Outlet Cathode Air Dew Point Temperature, F	52.0	51.6	50.0	52.2
Outlet Cathode Air Temperature, K	299.2	299.7	297.0	299.5
Outlet Cathode Air Temperature, F	79.0	79.8	75.0	79.5
Outlet Anode Gas Dew Point Temperature				
Observed, K	286.4	286.7	285.2	286.8
Observed, F	56.0	56.5	53.8	56.6
Calculated, K	286.4	286.6	285.2	286.7
Calculated, F	55.9	56.3	53.8	56.5

(a) CS-6 anode gas dew point data obtained during math model testing.

Should one of these four conditions occur, it is necessary to calculate what temperature the module will reach with the cooling air blowers in operating range (off to maximum capacity). The new module temperature is iteratively determined by solving the heat balance equations for cell voltage, heat generated, fin heat transfer coefficient, fin efficiency, heat removal by the gas streams, and the log mean temperature driving force for heat removal until the following two equations are satisfied:

$$DTREQ = DTAVA \quad (22)$$

$$HEATLOAD = \Delta H_{air} + \Delta H_{H_2} + \Delta H_{cool} \quad (23)$$

where

DTREQ = the required log mean ΔT driving force

DTAVA = the available log mean ΔT driving force

HEATLOAD = the heat generated

ΔH_{air} = the heat removed by the process (cathode) air

ΔH_{H_2} = the heat removed by the anode gas

ΔH_{cool} = the heat removed by the cooling air

Air Flow Correlation. Experimental data indicated that the correlation originally developed to predict CO_2 removal as a function of process (cathode) air flow rate required upgrading. The air flow correlation was therefore upgraded based on CS-6 performance data ⁽²⁾. The new correlation that was obtained is given by the equations

$$PA = (pCO_2) (V1/0.44N)^{f(pCO_2)} \quad (24)$$

$$f(pCO_2) = [1 + 0.84 (pCO_2)]e^{-0.84(pCO_2)} \quad (25)$$

where

PA = the normalized pCO_2 for air flow rate, mm Hg

N = the number of EDC cells

The normalized pCO_2 , PA, is then used in place of the actual pCO_2 in the CO_2 removal efficiency correlations.

Moisture Balance-Carbon Dioxide Removal Efficiency Correlation. The original EDC cell math model assumed that moisture was maintained within a preferred

operating range. The CO₂ removal efficiency correlation did not account for changes in CO₂ removal efficiency for moisture conditions outside the preferred range. Moisture conditions outside the preferred range occur since the module temperature to process air inlet dew point temperature differential (DELT1) control does not vary with changes in current and air flow rate. Hardware limitations in controlling DELT1 and improper setting of DELT1 also cause nonpreferred moisture balance conditions to occur. A correlation was therefore developed to account for changes in CO₂ removal efficiency as a function of moisture balance. The correlations derived from experimental data⁽⁵⁾ are given by the equation

$$TI^1 = TI [1 + 0.03536(DELT1 - 18.33)] \quad (26)$$

where

TI^1 = the Transfer Index corrected for moisture balance

TI = the noncorrected Transfer Index

The data that was used to derive the correlation is presented in Figure 18.

Computer Program

The CS-6 Base Program consists of a main program and eight subroutines. The main program manages input and output, directs calculation of heat and mass balances, checks for cooling and cathode air blower operation within range, checks for sufficient H₂ flow, checks plenum bypass flow, checks cell moisture conditions within tolerance, completes all stream definitions, and calculates total subsystem equivalent weight. The subroutines are called by the main program and by each other to calculate water vapor pressure from dew point temperature (PHTO), to calculate the dew point temperature from water vapor pressure (DEWT), to calculate TI (TICOR), to find the root of a function (ROOT), to calculate module temperature offset (TDRIFT), to calculate required and actual module cooling air temperature drops dependent upon module temperature (ERT1), to calculate required and actual module-cooling air temperature drops dependent upon cooling air flow rate (ERT), and to check input variable ranges(T).

Program Description

A detailed description of the program is presented in the main program flow chart and the subroutine flow charts, Appendix A. The program can be represented by ten major divisions for simplicity.

1. Read in and playback input data.
2. Check input ranges.
3. Check for sufficient H₂ flow and cathode blowers within range.

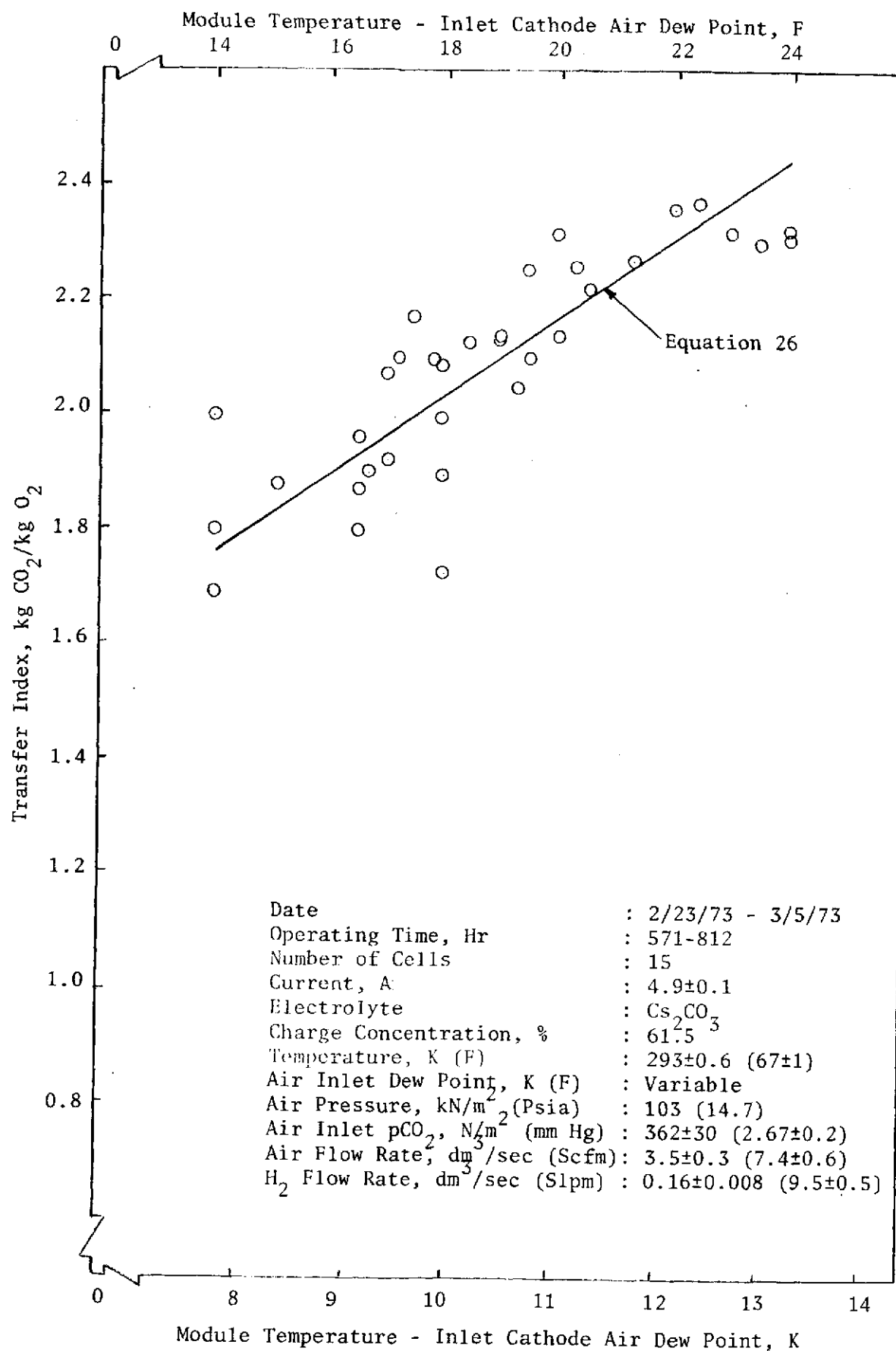


FIGURE 18 EFFECT OF MOISTURE CONDITIONS ON TRANSFER INDEX

4. Perform the heat balance including iterative solution governing module's heat load, cooling fin efficiency and heat transfer coefficient, cooling air flow rate, and module temperature.
5. Check the plenum bypass flow rate.
6. Calculate only stream parameters required for moisture balance checks.
7. Check module moisture conditions.
8. Complete all stream definitions.
9. Calculate subsystem equivalent weights.
10. Output results.

Also contained in Appendix A are the CS-6 Base Program Listing, the checks and messages performed by the program, and the nomenclature and units' definitions.

Program Assumptions

The following assumptions were made in developing the CS-6 Base Program:

1. Gas pressures are governed by the Ideal Gas Law and Dalton's Law.
2. Inlet H_2 flow rate greater than 1.3 times the stoichiometric amount does not affect TI.
3. Cabin air contains only N_2 , O_2 , CO_2 , and water in significant amounts.
4. Heat losses, leaks, and pressure drops in intercomponent lines are negligible.
5. The number of allowable cells in CS-6 is 90-96.
6. Pressure drops depend upon standard flow rates only, except in the H_2 sensor block and anode passages, where absolute pressure may differ significantly from atmospheric.
7. Transfer Index is proportional to a power of cathode air flow which approaches 1 as pCO_2 approaches 0, and diminishes to 0 as pCO_2 increases.
8. The dependence of TI upon moisture conditions is approximated by a linear function of the difference between module temperature and inlet cathode air dew point temperature.
9. Steady-state exists in the subsystem.
10. At least 5% of the inlet process air must pass through the plenum bypass to prevent backmixing of the outlet stream with the inlet stream.

11. The outlet H_2 dew point temperature is approximated by a weighted average of the module temperature, the inlet cathode air dew point, and the outlet cathode air dew point. Cathode air removes the remaining moisture produced.
12. Cooling air dampers remain closed when the cooling blowers are off.
13. When open, cooling dampers' pressure drop remains constant.
14. Heat loss of modules and blowers to the ambient air is negligible.
15. Primary controller, emergency controller, and data acquisition unit (DAU) reject waste heat only to the ambient.
16. Activation of valves is brief (less than one second) and adds no significant power penalty.
17. Cooling air blower power depends upon flow rate reaching a plateau and declining slightly at maximum flow. At lower flow rates, the power depends increasingly upon the plenum bypass pressure drop.
18. Cathode air blower power depends upon flow rate. The prediction range does not extend to very low flow rates, and the effect of differential pressure is neglected.
19. Cooling fin efficiency and heat transfer coefficient depend on cooling air flow rate only.
20. Differences between cells, modules, and sections are insignificant.
21. Inlet cooling air and inlet cathode air have the same temperature and pressure.

Program Features

The following features were incorporated into the CS-6 Base Program.

1. The program checks each set of input data to insure that each parameter is within its prediction range.
2. Cooling air flow rate is calculated for the set point module temperature. Under certain conditions, however, the subsystem hardware is unable to provide the required cooling air flow rate to control module temperature at the set point. These conditions are (1) insufficient blower capacity, (2) excessive cooling damper leakage, (3) insufficient cooling air temperature, and (4) insufficient module heat generation. For these conditions program logic calculates the temperature to which the modules would drift with the cooling blowers in range, and proceeds.
3. All significant pressure drops are calculated based on flow rates and, where appropriate, absolute pressure.

4. Inlet stream pressures are calculated based on outlet stream pressures and system pressure drops.
5. All significant component power consumptions and heat rejections are calculated. All intermediate streams are completely specified regarding temperature, pressure, composition, and flow rate.
6. Total subsystem equivalent weight is calculated from adjustable penalty factors for heat rejection, power consumption, O_2 consumption, and water rejection.
7. Input data may be entered directly from a terminal or from a previously prepared data file for convenience when a large number of problems are to be done during the same run.

Model Results

Sample problems were run using the CS-6 Base Program to verify the model's predictability for subsequent incorporation into the CS-6 Cabin pCO_2 Simulation Program. Output data from the program was checked against experimental data and the model upgraded throughout the development phase. Several sample outputs are presented in Appendix B. The results corresponded well to experimental data as expected since the major math model correlations (i.e., CO_2 removal efficiency, blower power, gas stream pressure drop, etc.) are empirically based.

CS-6 CABIN pCO_2 SIMULATION PROGRAM

The CS-6 Cabin pCO_2 Simulation Program is the computer program that was developed to simulate the steady-state spacecraft cabin pCO_2 profile resulting from the interaction of a repeating daily metabolic CO_2 generation profile and the CS-6 as the spacecraft CCS for a given cabin volume.

The program calculates and outputs cabin pCO_2 , CO_2 removal rate and efficiency, cell voltage, subsystem power requirements, subsystem equivalent weight, and other subsystem parameters as a function of time for a given CO_2 generation profile. A list of the input variable ranges and their units are presented in Table 7. The complete list of input and output variables and their units are presented in Table 8.

Model Analysis

The specific functions performed by the pCO_2 simulation program are to define Mode B (if required) from the input parameters and perform the integration over each time interval to calculate the change in cabin pCO_2 (for both Mode A and Mode B).

Mode B Definition

A typical Mode B control scheme is presented in Figure 19. Current and air flow vary linearly with cabin pCO_2 . Two sets of input data are used to define Mode B; the minimum and maximum pCO_2 levels and their corresponding current and air

TABLE 7 CS-6 CABIN pCO_2 SIMULATION PROGRAM
INPUT VARIABLE RANGES

Cabin Atmosphere	
Total Pressure, P \emptyset PSA	13.7-15.7 Psia
pCO_2 , PC \emptyset	0.0001-10 mm Hg
pO_2 , PO \emptyset PSA	2-4 Psia
Temperature, T \emptyset	44-80F
Volume, VOLUME	10 ² -10 ⁵ Ft ³
Process Air Outlet	
Total Pressure, P8PSA	13.7-15.7 Psia
Process Air Inlet	
Temperature, T7	44-80F
Flow Rate, V7	0-600 Scfm ^(a)
Dew Point Temperature, DW7	41-70F
Anode H ₂ /CO ₂ Outlet	
Total Pressure, P4PSA	14.8-21.2 Psia
System H ₂ Inlet	
Temperature, T9	65-75F
Flow Rate, V9SL	0-18 Scfm ^(a)
Dew Point Temperature, DW9	10-75F
Modules	
Number in Circuit, N	90-96
Current, I	2.44-9.76 A
DELT1 ^(b)	10-25F
Cathode Air Flow Rate, V1	5.0-76.8 Scfm (96 cells)
Penalty Weight Factors	
Power, PWPEN	0-2 Lb/Watt
Heat Rejection to Ambient, HTPEN	0-2 Lb/Btu/Hr
Water Vapor Rejection to Ambient, H2OPEN	0-500 Lb/Lb H ₂ O/Hr
Oxygen Consumption, OXPEN	0-3000 Lb/Lb O ₂ /Hr
Program Control	
KMODE ^(c)	0-1
NFLAG ^(d)	0-1
Minimum Current, BK(1)	2.44-9.76 A

(a) Reference conditions for standard flow units: 70F, 14.7 Psia

(b) DELT1 = Module temperature - cathode air inlet dew point temperature

(c) KMODE = 0 Mode A

1 Mode B

(d) NFLAG = 0 Out of tolerance moisture conditions do not stop program.

1 Out of tolerance moisture conditions do stop program.

-continued-

Table 7 - continued

pCO ₂ for Minimum Current, BK(2)	0.0001-10 mm Hg
pCO ₂ for Maximum Current, BK(3)	0.0001-10 mm Hg
Maximum Current, BK(4)	2.44-9.76 A
Minimum Cathode Air Flow Rate, BK(5)	5.0-76.8 Scfm
pCO ₂ at Minimum Cathode Air Flow Rate, BK(6)	0.0001-10 mm Hg
pCO ₂ at Maximum Cathode Air Flow Rate, BK(7)	0.0001-10 mm Hg
Maximum Cathode Air Flow Rate, BK(8)	5.0-76.8
Number of Days to be Simulated, DAYS	0-10 Days (a)
Integration Time Increment, DT	1-15 Minutes (b)
Output Table Time Increment, DPRINT	1-100 Minutes

(a) DT must be chosen so that the length of each time step in the CO₂ generation rate table is a whole multiple of DT.

(b) DPRINT must be a whole multiple of DT.

TABLE 8 CS-6 CABIN $p\text{CO}_2$ SIMULATION PROGRAM
INPUT AND OUTPUT VARIABLES

Input Variables

Cabin Atmosphere	Total Pressure, Psia $p\text{CO}_2$, mm Hg $p\text{O}_2$, Psia Temperature, F Volume, Ft ³
Process Air Outlet	Total Pressure, Psia
Process Air Inlet	Temperature, F Flow Rate, Scfm Dew Point Temperature, F
Anode H_2/CO_2 Outlet	Total Pressure, Psia
Anode H_2 Inlet	Temperature, F Flow Rate, Slpm Dew Point Temperature, F
Modules	Number of Cells in Circuit Current, A DELTI, F Cathode Air Flow Rate, Scfm
Penalty Weight Factors	Power Consumption, Lb/Watt Heat Rejection, Lb/Btu/Hr Water Vapor Rejection, Lb/Lb/Hr O_2 Consumption, Lb/Lb/Hr
Control	KMODE 0 = Mode A, 1 = Mode B NFLAG 0 = ignore out-of-tolerance moisture conditions 1 = abort for out-of-tolerance moisture conditions
Mode B	Minimum Current, A $p\text{CO}_2$ for Minimum Current, mm Hg $p\text{CO}_2$ for Maximum Current, mm Hg Maximum Current, A Minimum Cathode Airflow, Scfm $p\text{CO}_2$ for Minimum Airflow, mm Hg $p\text{CO}_2$ for Maximum Airflow, mm Hg Maximum Cathode Airflow, Scfm Maximum Number of Days to be Integrated, Day Integration Increment, Min Printing Increment, Min

Output Variables

Control	Preferred Value of DELTI ^(a) , F
---------	---

-continued-

(a) DELTI = Module Temperature - Inlet Cathode Air
Dew Point Temperature

Table 8 - continued

Module	Transfer Index, Lb CO ₂ /Lb O ₂ Transfer Efficiency, % Cell Voltage, V Module Voltage, V CO ₂ Removal Rate, Lb/Hr O ₂ Consumption Rate, Lb/Hr H ₂ Consumption Rate, Lb/Hr Water Production Rate, Lb/Hr Current Density, A/Ft ² Heat Load Modules, Btu/Hr Power Production of Modules, Watt
Cathode Air Inlet	Total Pressure, mm Hg pCO ₂ , mm Hg pH ₂ O, mm Hg CO ₂ Flow Rate, Lb/Hr Water Flow Rate, Lb/Hr CO ₂ Flow Rate, Scfm Water Flow Rate, Scfm O ₂ Flow Rate, Scfm N ₂ Flow Rate, Scfm Temperature, F Dew Point Temperature, F Relative Humidity, %
Cathode Air Outlet	Total Pressure, mm Hg Module Cathode Air Pressure Drop, mm Hg pCO ₂ , mm Hg pH ₂ O, mm Hg Total Flow Rate, Scfm CO ₂ Flow Rate, Scfm Water Flow Rate, Scfm O ₂ Flow Rate, Scfm N ₂ Flow Rate, Scfm CO ₂ Flow Rate, Lb/Hr Water Flow Rate, Lb/Hr Temperature, F Dew Point Temperature, F Relative Humidity, % Cathode Air Blower Outlet Total Pressure, mm Hg Cathode Air Blower Outlet Flow Rate, Scfm Cathode Air Blower Outlet Temperature, F
Process Air Inlet	Total Pressure, mm Hg pH ₂ O, mm Hg pN ₂ , mm Hg CO ₂ Flow Rate, Scfm Water Flow Rate, Scfm

Table 8 - continued

	O ₂ Flow Rate, Scfm
	N ₂ Flow Rate, Scfm
	Dew Point Temperature, F
	Relative Humidity, %
Process Air Outlet	Total Pressure, mm Hg
	pCO ₂ , mm Hg
	Plenum Bypass Flow Rate, Scfm
	Plenum Bypass Pressure Drop, mm Hg
	Total Flow Rate, Scfm
	Water Flow Rate, Scfm
	CO ₂ Flow Rate, Scfm
	O ₂ Flow Rate, Scfm
	pH ₂ O, mm Hg
	Temperature, F
	Dew Point Temperature, F
	Relative Humidity, %
H ₂ Inlet	Total Pressure, mm Hg
	Water Vapor Pressure, mm Hg
	Distribution Block Pressure and Drop, mm Hg
	Module Inlet Total Pressure, mm Hg
	Module Inlet pH ₂ O, mm Hg
	Module Inlet pH ₂ , mm Hg
	Total Flow Rate, Scfm
	H ₂ Flow Rate, Scfm
	Water Flow Rate, Scfm
	H ₂ Flow Rate, Lb/Hr
	Minimum Required Flow Rate, Slpm
H ₂ Outlet	Total Pressure, mm Hg
	Module Anode Gas Pressure Drop, mm Hg
	Water Vapor Pressure, mm Hg
	Flow Rate, Scfm
	CO ₂ Flow Rate, Scfm
	H ₂ Flow Rate, Scfm
	Water Flow Rate, Scfm
	Flow Rate, Slpm
	CO ₂ Flow Rate, Slpm
	H ₂ Flow Rate, Slpm
	Total Flow Rate, Lb/Hr
	CO ₂ Flow Rate, Lb/Hr
	H ₂ Flow Rate, Lb/Hr
	Water Flow Rate, Lb/Hr
	Dew Point Temperature, F
	CO ₂ -H ₂ Weight, Lb CO ₂ /Lb H ₂
	H ₂ -CO ₂ Volume Ratio, Slpm H ₂ /Slpm CO ₂

Table 8 - continued

Heat Balance, Modules

Modules Heat Load, Btu/Hr
Cathode Air Heat Pickup, Btu/Hr
Anode Gas Heat Pickup, Btu/Hr
Cooling Air Heat Pickup, Btu/Hr

Cooling Air

Inlet Pressure, mm Hg
Coolant Channel Pressure Drop, mm Hg
Outlet Pressure, mm Hg
Flow Rate, Scfm
Inlet Temperature, F
Outlet Temperature, F
Heat Transfer Coefficient, Btu/Hr/Ft²/F
Fin Efficiency, %
Flow Rate Over Cells in Circuit, Scfm
In Circuit Outlet Temperature, F
Cooling Blower Outlet Pressure, mm Hg
Cooling Blower Outlet Flow Rate, Scfm
Cooling Blower Outlet Temperature, F
Cooling Damper Pressure Drop, mm Hg
Minimum Leakage Flow Rate, Scfm

Actual Volumetric Flow Rates

Modules Cathode Air Inlet, Cfm
Modules Cathode Air Outlet, Cfm
Modules H₂ Inlet, Cfm
Modules H₂-CO₂ Outlet, Cfm
Modules Cooling Air Inlet, Cfm
Modules Cooling Air Outlet, Cfm
Modules Cooling Air Outlet From Cells
in Circuit, Cfm
Process Air Inlet, Cfm
Process Air Outlet, Cfm
System H₂ Inlet, Cfm
Process Air Plenum Bypass Outlet, Cfm
Cathode Air Blowers Outlet, Cfm
Cooling Blowers Outlet, Cfm
Cooling Dampers Outlet, Cfm

Equivalent Weight

Cooling Blower Power, Watt
Cathode Blower Power, Watt
Primary Controller Power, Watt
Emergency Controller Power, Watt
Data Acquisition Unit Power, Watt
Total System Power, Watt
Total Heat Rejection, Btu/Hr
Power Consumption Penalty Weight, Lb
Heat Rejection Penalty Weight, Lb
Water Vapor Rejection Penalty Weight, Lb
O₂ Consumption Penalty Weight, Lb
Hardware Weight, Lb
Total Equivalent Weight, Lb

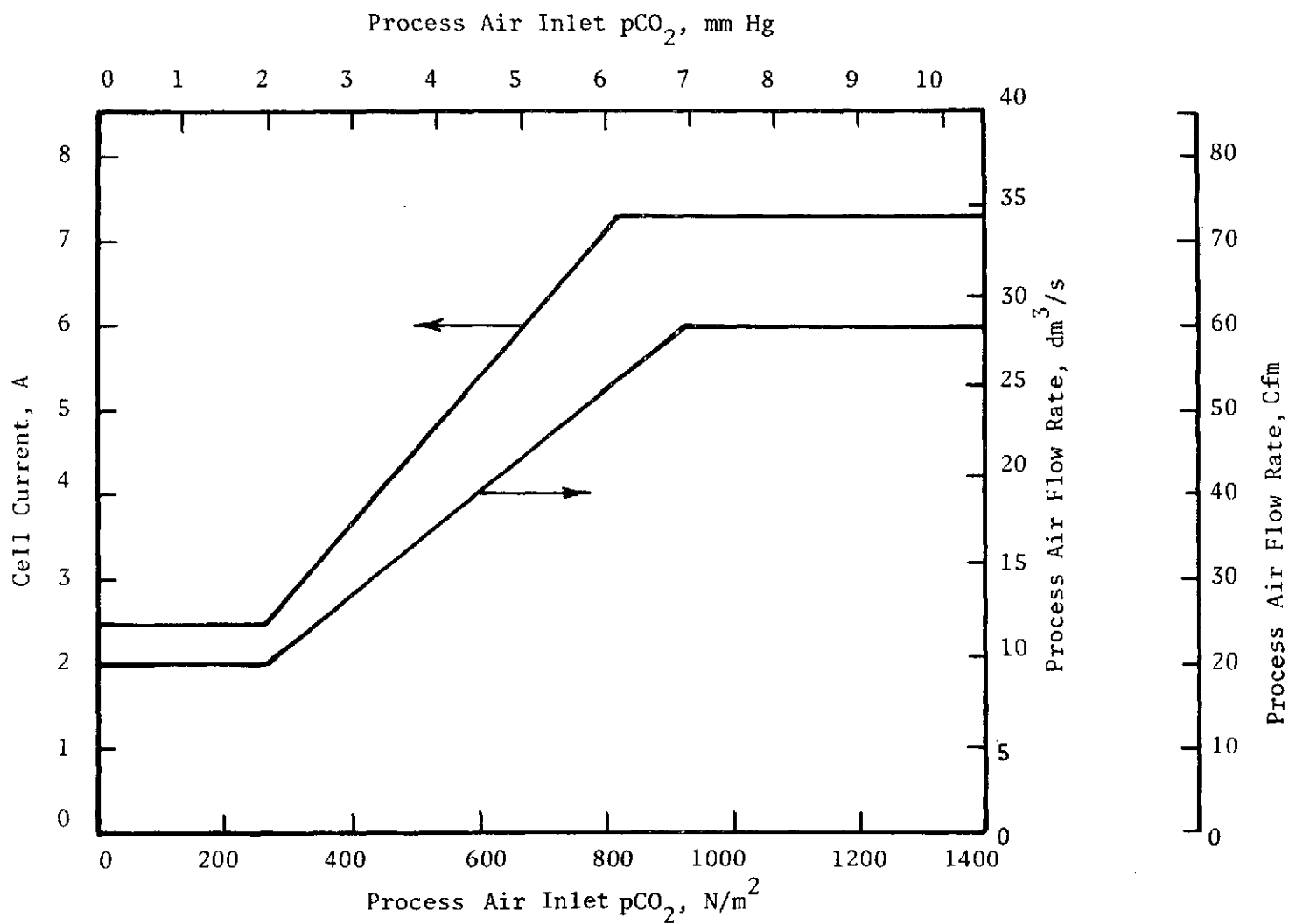


FIGURE 19 CONTROL MODE B (TYPICAL)

flow rates. The program takes the two sets of inputs, determines the slope and intercept for each set of inputs, and defines the equations for current and air flow as a function of $p\text{CO}_2$. These equations are then used in the $p\text{CO}_2$ integration when control Mode B is requested.

Cabin $p\text{CO}_2$ Integration

To obtain the cabin $p\text{CO}_2$ as a function of time, the main program performs a mass balance on CO_2 in the cabin for each of the integration intervals. Each mass balance yields the $p\text{CO}_2$ value at the end of the interval. The $p\text{CO}_2$ at the end of the interval depends upon the average net CO_2 removal rate during the interval, but the average removal rate depends upon the $p\text{CO}_2$ at the end of the interval. Neither value is known initially, therefore an iterative solution is necessary.

The equations which must be satisfied in the mass balance are:

$$P(t) = P(t-\Delta t) + \frac{1}{2} \left(\left. \frac{dp}{dt} \right|_t + \left. \frac{dp}{dt} \right|_{t-\Delta t} \right) \Delta t \quad (27)$$

$$\left. \frac{dp}{dt} \right|_t = k [G(t) - R(P(t))] \quad (28)$$

where

P = cabin $p\text{CO}_2$

t = time

Δt = integration increment

k = proportionality constant between net removal rate of CO_2 and cabin $p\text{CO}_2$

G = CO_2 generation rate, a function of time only, calculated by the main program

R = CO_2 removal rate, a function of cabin $p\text{CO}_2$ only, calculated by the CS-6 BASE subroutine

The use of the arithmetic average derivative in Equation 27 is the same approximation used in Simpson's Rule Integration. The error vanishes when the function $P(t)$ is parabolic over the interval.

All variables are known for time $t-\Delta t$ when the integration begins. An approximation for $P(t)$ is substituted into Equation 28 and solved using the CS-6 BASE subroutine. The result is substituted into Equation 27 to recalculate $P(t)$. The correct $P(t)$ is found when the approximate and the recalculated values of $P(t)$ agree. For the first approximation labeled "1" in Figure 20, it is assumed that $P(t)$ equals $P(t - \Delta t)$.

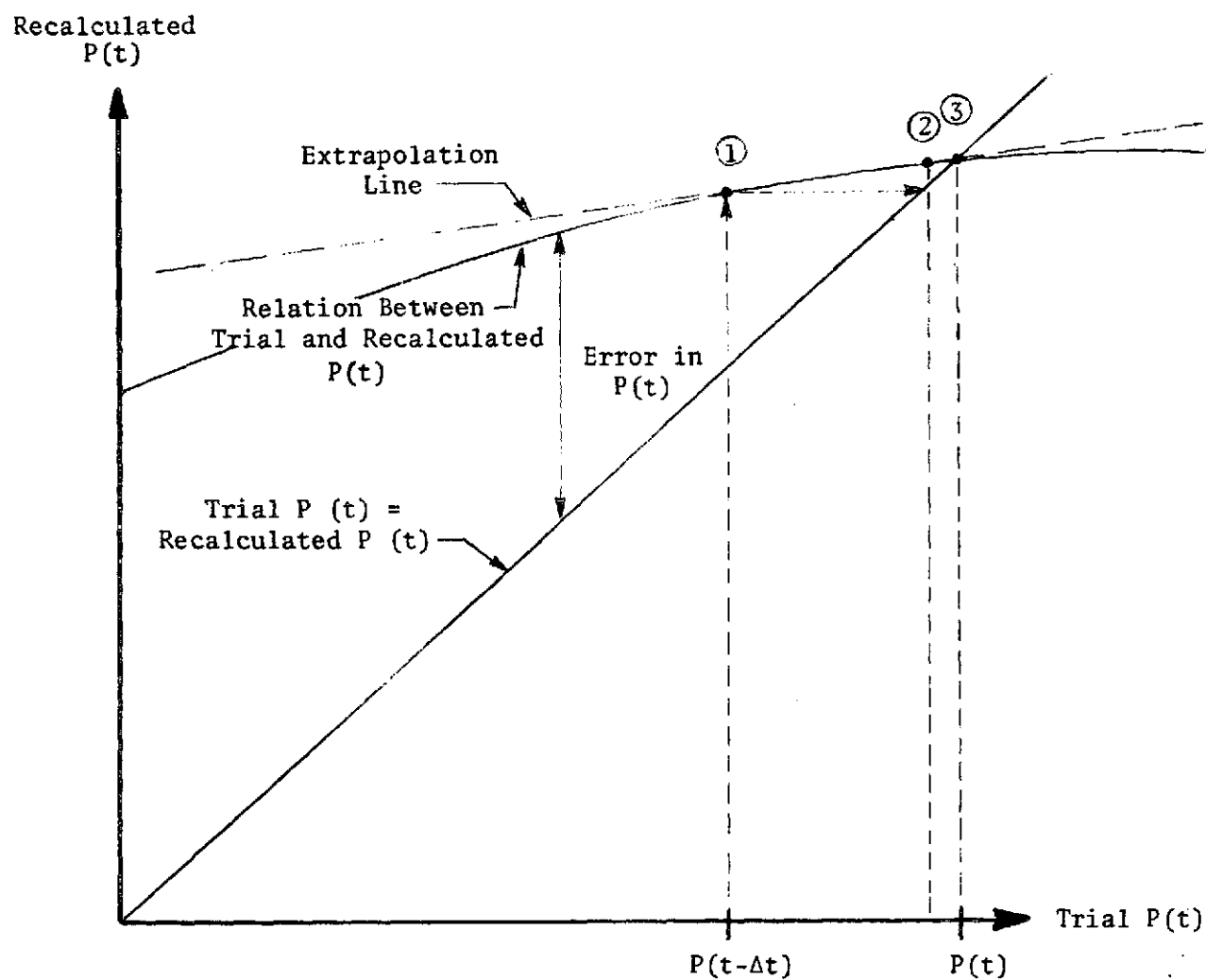


FIGURE 20 GRAPHIC REPRESENTATION OF CONVERGENCE SCHEME

The first trial value is substituted into Equations 27 and 28, giving a recalculated value. This value is then used as the second trial value of $P(t)$, labeled "2" in Figure 20. The relation between trial and recalculated $P(t)$ is close to linear when the time increments are 15 minutes or less. The final P value, labeled "3" in Figure 20, is at the intersection of the secant through points 1 and 2, and the 45 degree line.

The BASE subroutine is called for the second and third values of P only. It is not necessary for the first trial, which assumes constant pCO_2 , since the CO_2 removal rate would then also be constant. Each integration increment requires only two subroutine calls with the convergence scheme used, compared to ten or more with schemes such as interval halving.

Computer Program

The CS-6 Cabin pCO_2 Simulation Program consists of the main program and a number of subroutines. The main program manages input and output and performs integration of net CO_2 removal to calculate the cabin pCO_2 profile. The BASE subroutine (the CS-6 Base Program adapted with minor modifications) provides all the CS-6 parameters to the main program, including CO_2 removal rate. Subroutines are utilized primarily by the BASE subroutine to relate water vapor pressure and dew point temperature, to calculate the CO_2 Transfer Index (TI), to find the root of a function, to calculate temperatures and flow rates, to satisfy subsystem heat balance, to check input parameters against their allowable ranges, and to calculate current and cathode air flow rate for Mode B CS-6 operation.

Program Description

A detailed description of the CS-6 Cabin pCO_2 Simulation Program is presented in the main program flow chart and the subroutine flow charts, Appendix C. The program can be divided into 14 major subdivisions for simplicity.

1. Determine input/output devices.
2. Read and write problem identifier.
3. Read in and print out (if desired) CO_2 generation table.
4. Read inputs for CS-6 BASE subroutine, Mode B parameters, integration and print out parameters.
5. Determine whether table describing CS-6 at time zero is to be printed, and input subscripts for selected variables to be printed as they vary with time.
6. Calculate Mode B parameters.
7. Print out input data.
8. Check inputs and print names of any that are outside the prediction ranges.

9. Print description at time zero if desired.
10. Print headings for table.
11. Call BASE to perform $p\text{CO}_2$ integration over one or more intervals until printing interval is reached.
12. Print a line in the table.
13. Continue from Step 11 unless it is the end of the day.
14. Continue from Step 2 if steady-state has been reached or if the maximum number of days has been integrated, otherwise continue from Step 10 to integrate $p\text{CO}_2$ for an additional day.

Appendix C also contains the program listing, program checks and messages, nomenclature and units, and the key to select output variables.

Program Assumptions

The following assumptions were made in the development of the CS-6 Cabin $p\text{CO}_2$ Simulation Program.

1. The CO_2 generation profile is a step function of time only.
2. Each step in the CO_2 generation profile is an integer number of minutes.
3. Module set point temperature, an input, does not change during the day. It is not a function of current density or air flow in either Mode A or B.
4. Cabin air is uniform in composition at any time.
5. The Ideal Gas Law applies to the cabin air.
6. The cabin air contains O_2 , N_2 , CO_2 , and water vapor only.
7. Cabin $p\text{H}_2\text{O}$, $p\text{O}_2$, and total pressure are constant; $p\text{N}_2$ and $p\text{CO}_2$ vary.
8. The $p\text{CO}_2$ integration time increment, an integer number of minutes, is chosen so that each CO_2 generation step contains an integer number of increments.
9. In Mode B operation, current density and cathode air flow are linear functions of cabin $p\text{CO}_2$ but are bounded by minimum and maximum values.
10. The graph of cabin $p\text{CO}_2$ versus time can be represented by a series of parabolic segments.

Program Features

The following features were incorporated into the CS-6 Cabin pCO₂ Simulation Program:

1. The input items are checked by the program to insure that all are within the prediction ranges.
2. Input may be entered directly from a terminal to take full advantage of operator-program interaction, or from a previously prepared data file for convenience when a large number of runs are to be done at once.
3. Output may be printed directly at the terminal or written in one or more data files for convenience when a large amount of data is involved.
4. A program option allows a table containing all subsystem parameters, both constant and time dependent, to be either printed or omitted at time zero of the simulation.
5. Any number of the subsystem parameters may be selected for printing as they vary at simulated time intervals.
6. The pCO₂ integration performed by the main program combines maximum usage of past values of pCO₂ with an interpolation algorithm so that the BASE subroutine is required only twice during each simulated time interval. The first time, only enough of the BASE subroutine is executed to yield a trial CO₂ removal rate and check for achievement of steady-state in the CS-6. The second call of the BASE subroutine is extended only enough to calculate the final CO₂ removal rate, the other selected subsystem parameters, and to verify steady-state in the CS-6. These techniques have caused the calculation portion of the program to consume less computing time than the printing of results. Integration accuracy is four significant figures, minimum.

Model Results

The CS-6 Cabin pCO₂ Simulation Program was used to predict the cabin pCO₂ profile and selected CS-6 performance parameters for control Modes A and B. The CO₂ generation profile used for the runs is presented in Figure 21. Sample outputs for the pCO₂ Simulation Program are presented in Appendix D.

Sample cases for control Mode A were run to obtain the steady-state pCO₂ profile that would result, given initial cabin pCO₂ levels of 0 and 1333 N/m² (0 and 10 mm Hg). The results of three typical runs are presented in Figures 22, 23, and 24 for 4.88A, Mode A (1), 3.66A, Mode A (2), and 7.32A, Mode A (3), respectively. The remaining input parameters are presented in Table 9. Similar sample cases for control Mode B were run for initial pCO₂ levels of 0 and 1333 N/m² (0 and 10 mm Hg). The pCO₂ profiles for four typical sets of Mode B parameters (Table 10) are presented in Figures 25 through 28. The remaining Mode B inputs are presented in Table 11.

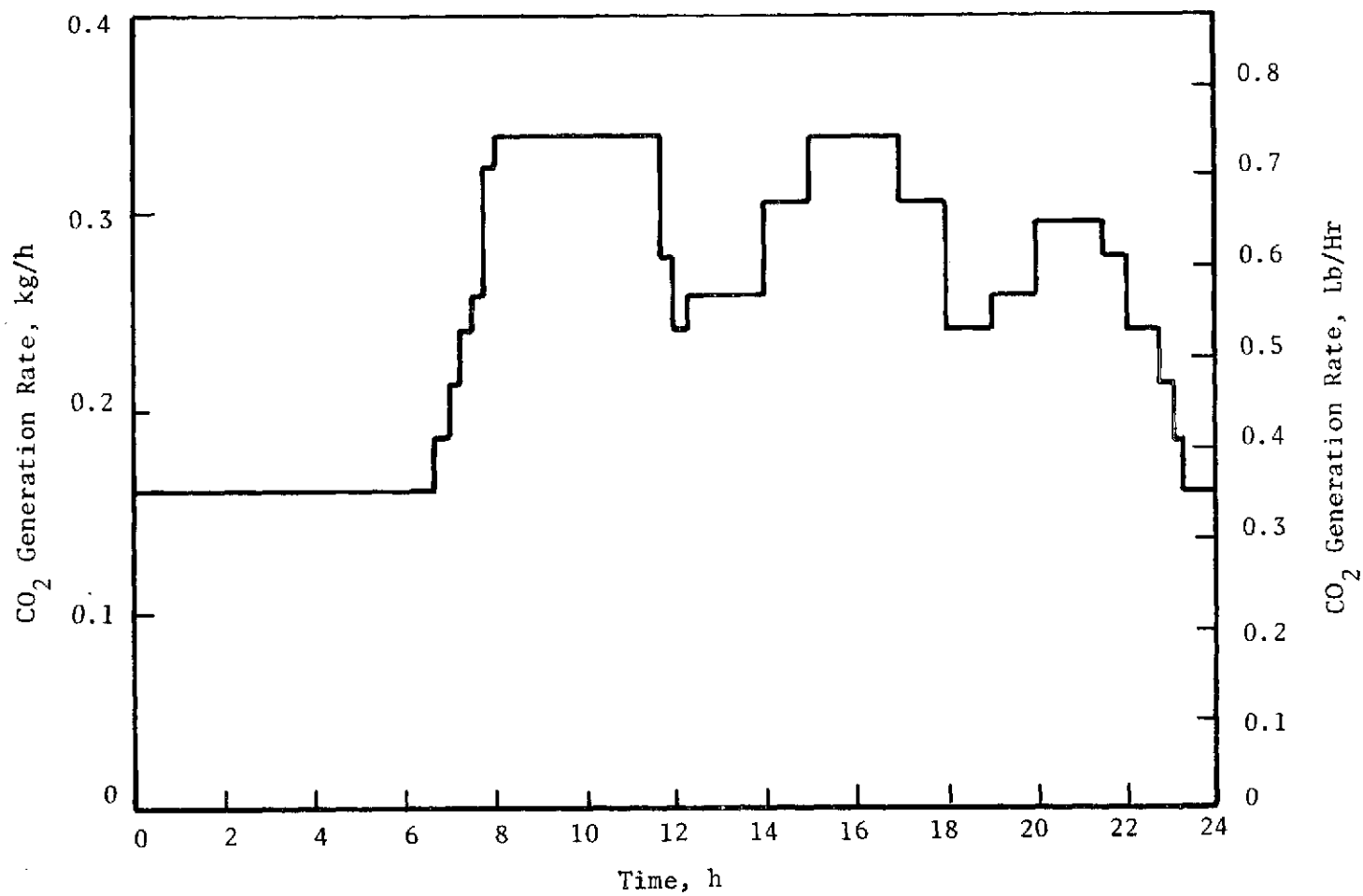


FIGURE 21 CABIN CO₂ GENERATION RATE PROFILE

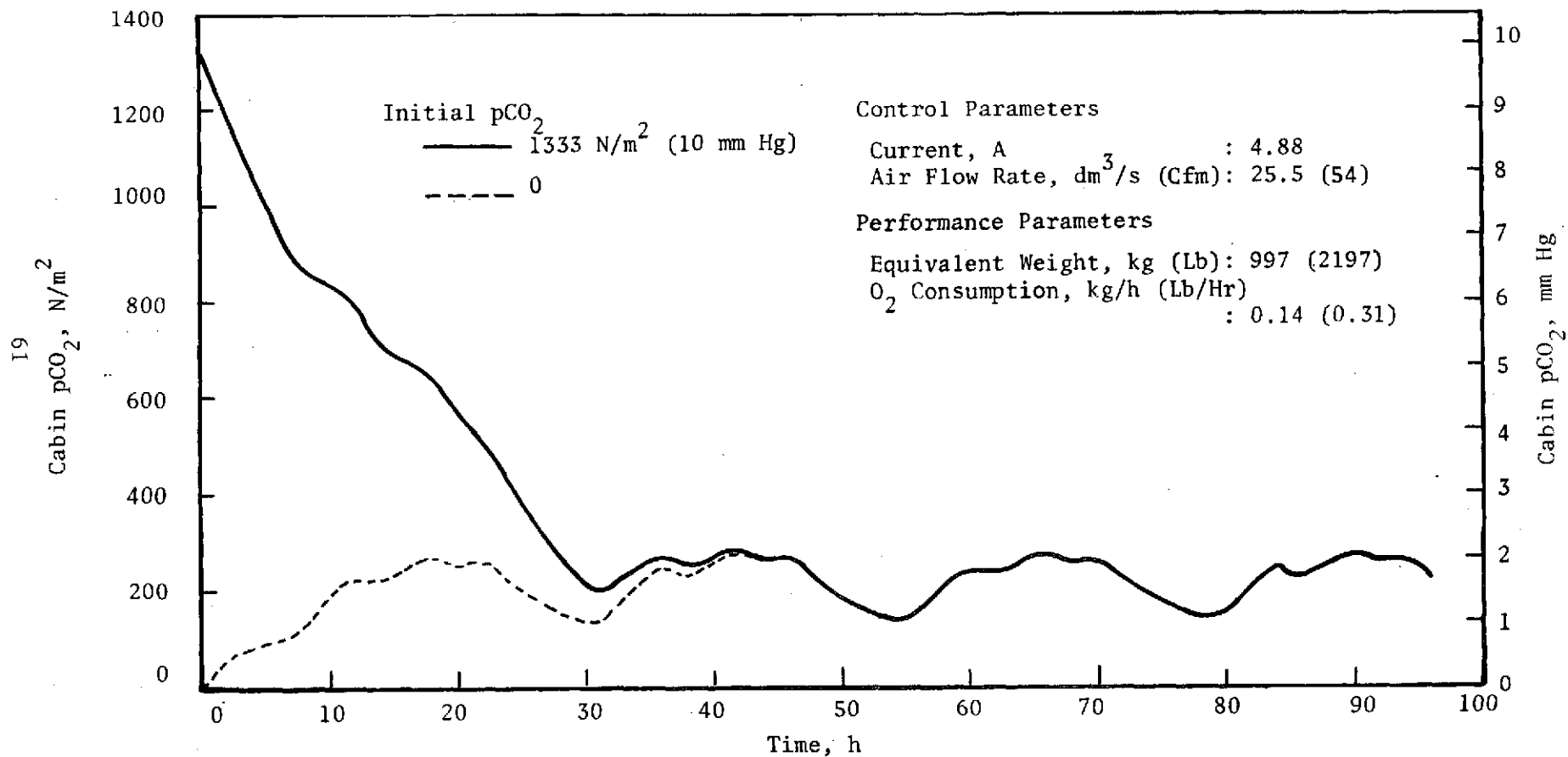
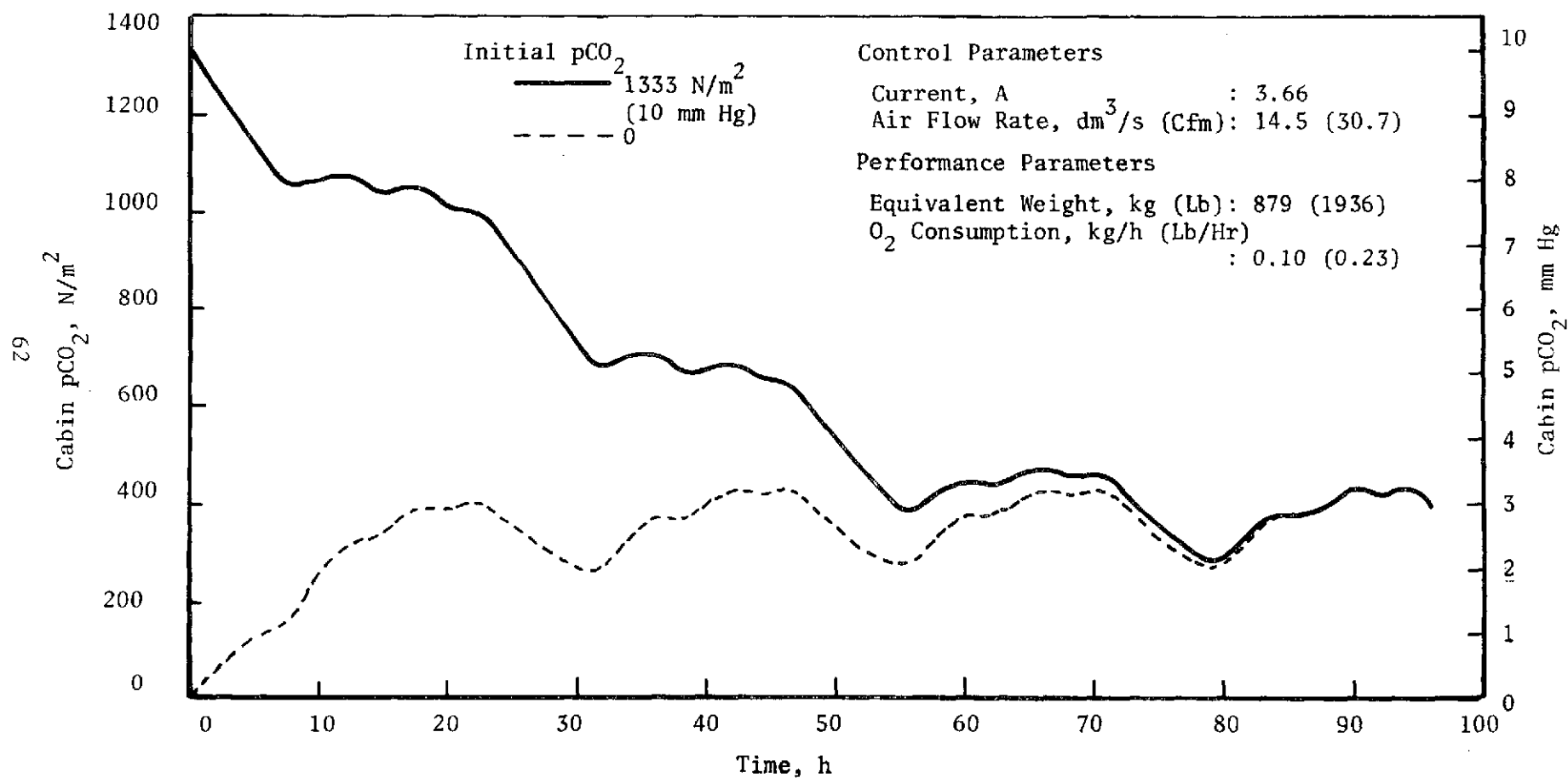


FIGURE 22 CABIN $p\text{CO}_2$ SIMULATION PROFILE FOR CONTROL MODE A(1)

FIGURE 23 CABIN $p\text{CO}_2$ SIMULATION PROFILE FOR CONTROL MODE A(2)

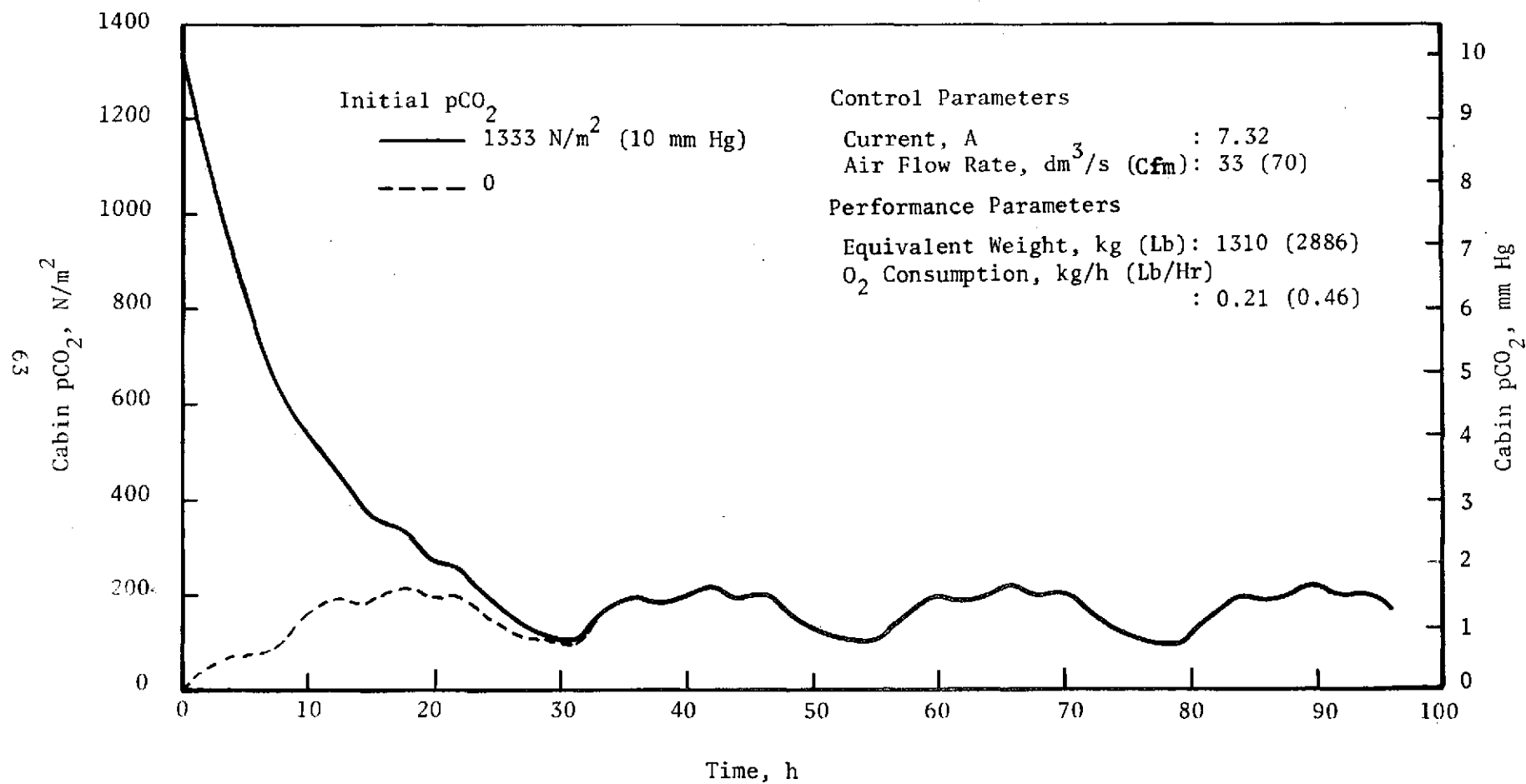


FIGURE 24 CABIN $p\text{CO}_2$ SIMULATION PROFILE FOR CONTROL MODE A(3)

TABLE 9 INPUT VARIABLES FOR SAMPLE MODE A PROBLEMS

Cabin Atmosphere	
Total Pressure, P \emptyset PSA	14.7 Psia
pCO ₂ , PC \emptyset	0.001, 10 mm Hg
pO ₂ , PO \emptyset PSA	3.1 Psia
Temperature, T \emptyset	70F
Volume, VOLUME	8000 Ft ³
Process Air Outlet	
Total Pressure, P8PSA	14.75 Psia
Process Air Inlet	
Temperature, T7	55F
Flow Rate, V7	500 Scfm ^(a)
Dew Point Temperature, DW7	50F
Anode H ₂ /CO ₂ Outlet	
Total Pressure, P4PSA	20 Psia
System H ₂ Inlet	
Temperature, T9	72F
Flow Rate, V9SL	10 Scfm ^(a)
Dew Point Temperature, DW9	69F
Modules	
Number in Circuit, N	96
Current, I	4.00, 3.66, 7.32 A
DELT1 ^(b)	22F
Cathode Air Flow Rate, V1	54, 30.7, 70 Scfm (96 cells)
Penalty Weight Factors	
Power, PWPEN	0.591 Lb/Watt
Heat Rejection to Ambient, HTPEN	0.128 Lb/Btu/Hr
Water Vapor Rejection to Ambient, H2OPEN	134 Lb/Lb H ₂ O/Hr
Oxygen Consumption, OXPEN	1536 Lb/Lb O ₂ /Hr
Program Control	
KMODE ^(c)	0
NFLAG ^(d)	1
Number of Days to be Simulated, DAYS	4 Days ^(e)
Integration Time Increment, DT	15 Min ^(f)
Output Table Time Increment, DPRINT	60 Min

(a) Reference conditions for standard flow units: 70F, 14.7 Psia

(b) DELT1 = Module temperature - cathode air inlet dew point temperature

(c) KMODE = 0 - Mode A; 1 - Mode B

(d) NFLAG = 0 - Out-of-tolerance moisture conditions do not stop program
1 - Out-of-tolerance moisture conditions do stop program

(e) DT must be chosen so that the length of each time step in the CO₂ generation rate table is a whole multiple of DT

(f) DPRINT must be a whole multiple of DT

TABLE 10 CONTROL MODE B PARAMETERS

<u>Control Parameter</u>	<u>B(1)</u>	<u>B(2)</u>	<u>B(3)</u>	<u>B(4)</u>
Minimum Current, BK(1), A	2.586	2.586	2.586	2.586
pCO ₂ for Minimum Current, BK(2), mm Hg	2.5	1.0	1.0	2.5
pCO ₂ for Maximum Current, BK(3), mm Hg	2.8	2.8	10.0	10.0
Maximum Current, BK(4), A	6.6	6.6	6.6	6.6
Minimum Cathode Air Flow Rate, BK(5), Scfm	20	20	20	20
pCO ₂ at Minimum Cathode Air Flow Rate, BK(6), mm Hg	2.5	1.0	1.0	2.5
pCO ₂ at Maximum Cathode Air Flow Rate, BK(7), mm Hg	2.8	2.8	10.0	10.0
Maximum Cathode Air Flow Rate, BK(8), Scfm	60	60	60	60

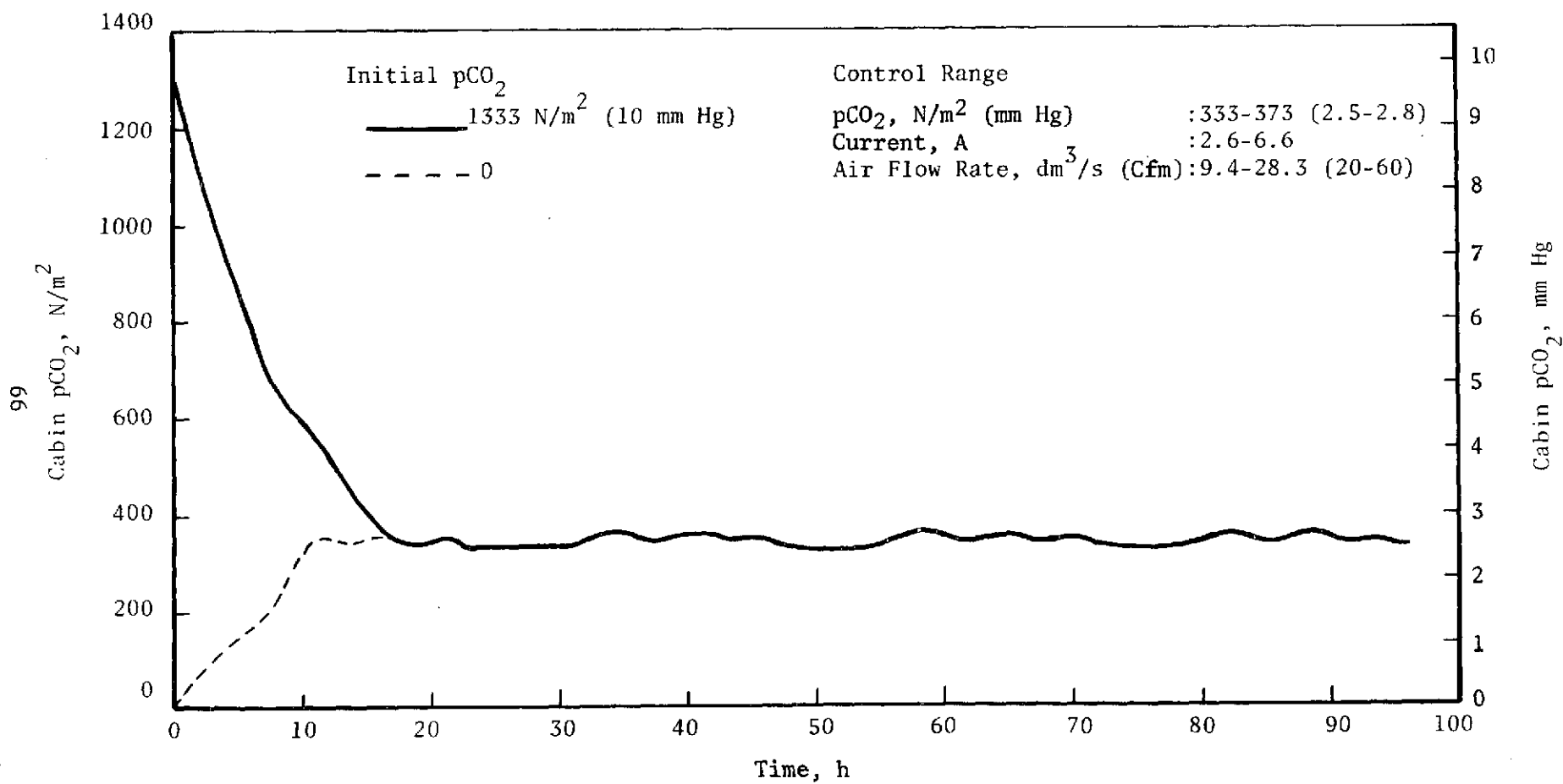


FIGURE 25 CABIN pCO_2 SIMULATION PROFILE FOR CONTROL MODE B(1)

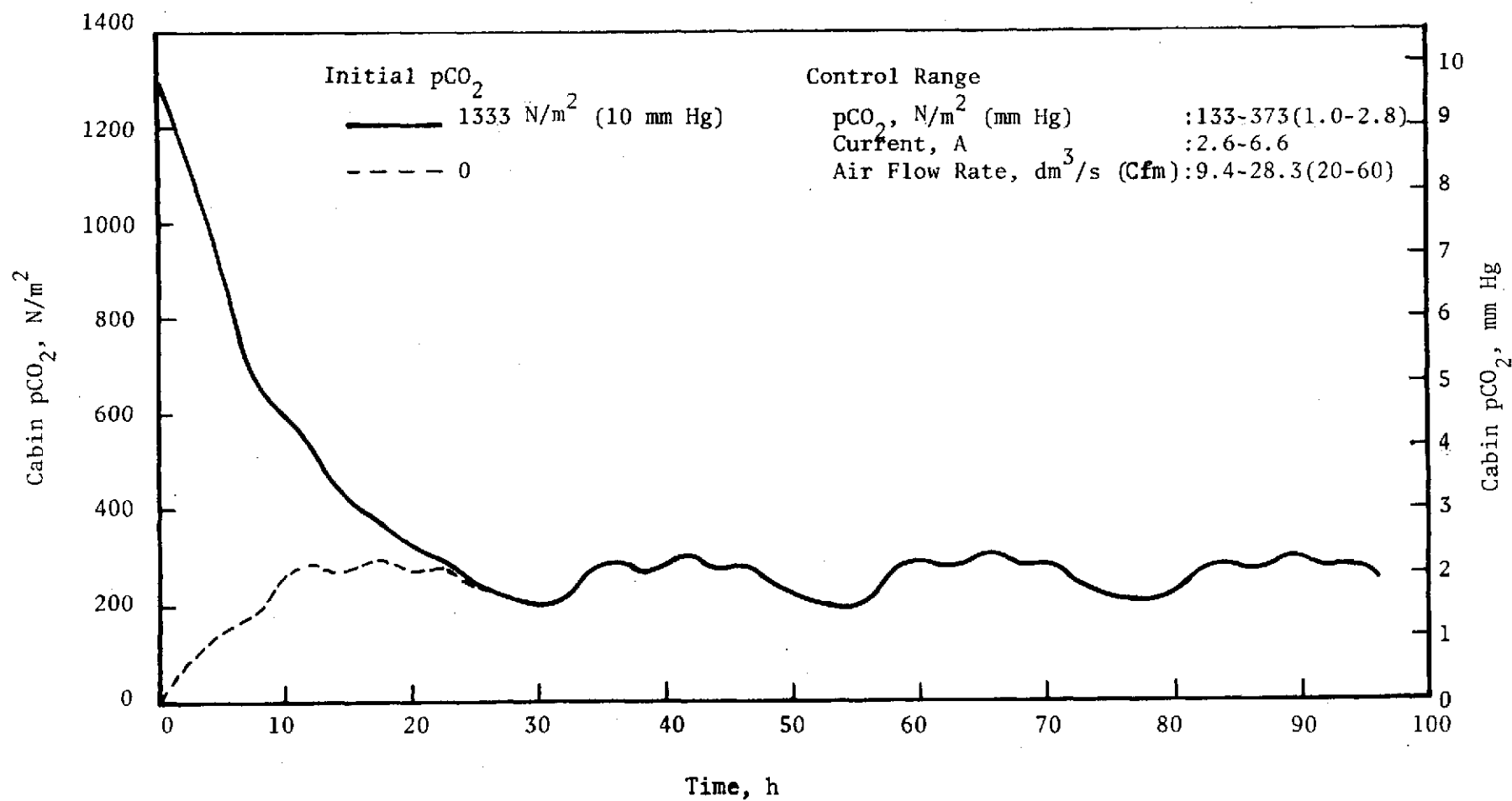
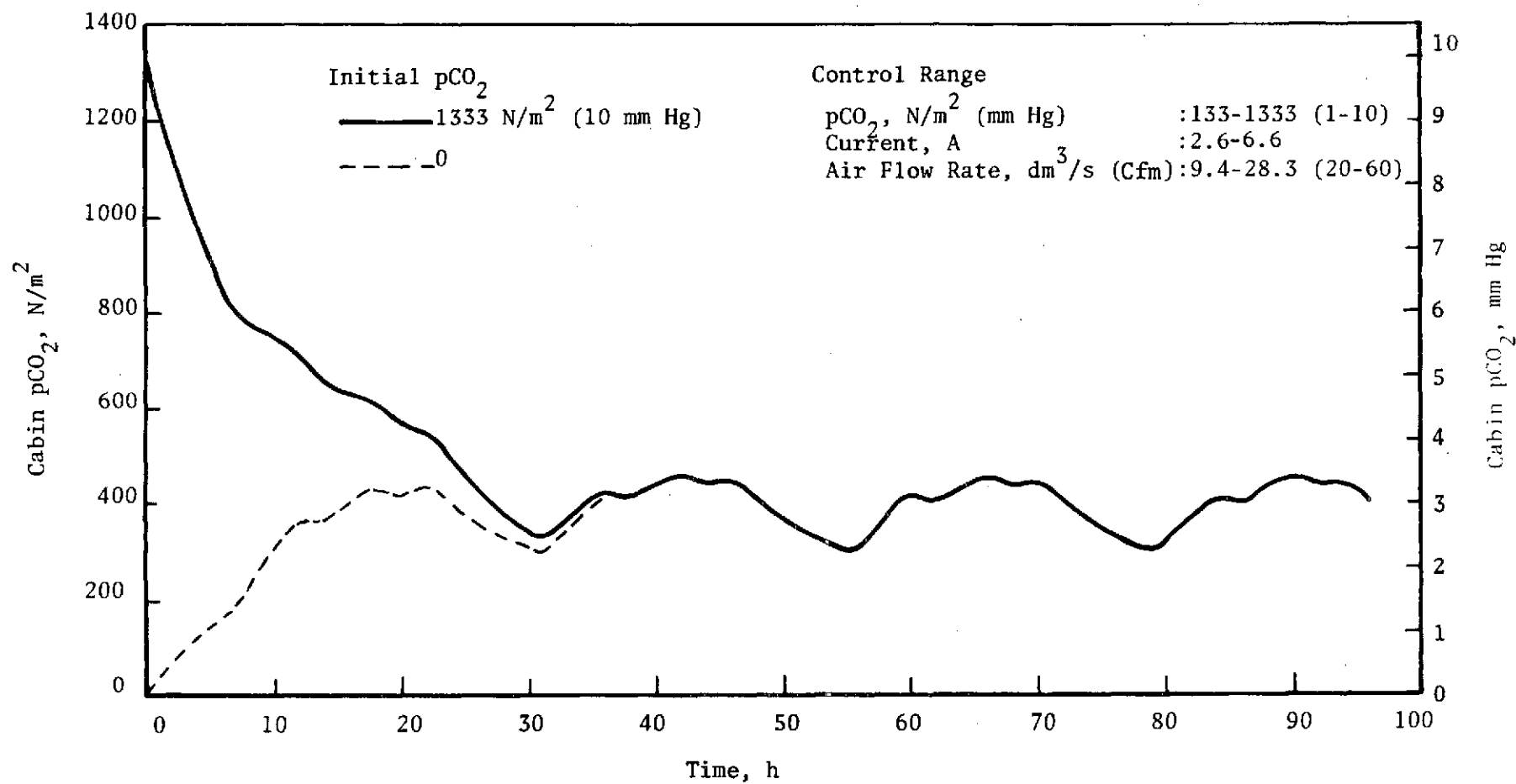


FIGURE 26 CABIN $p\text{CO}_2$ SIMULATION PROFILE FOR CONTROL MODE B(2)

FIGURE 27 CABIN $p\text{CO}_2$ SIMULATION PROFILE FOR CONTROL MODE B(3)

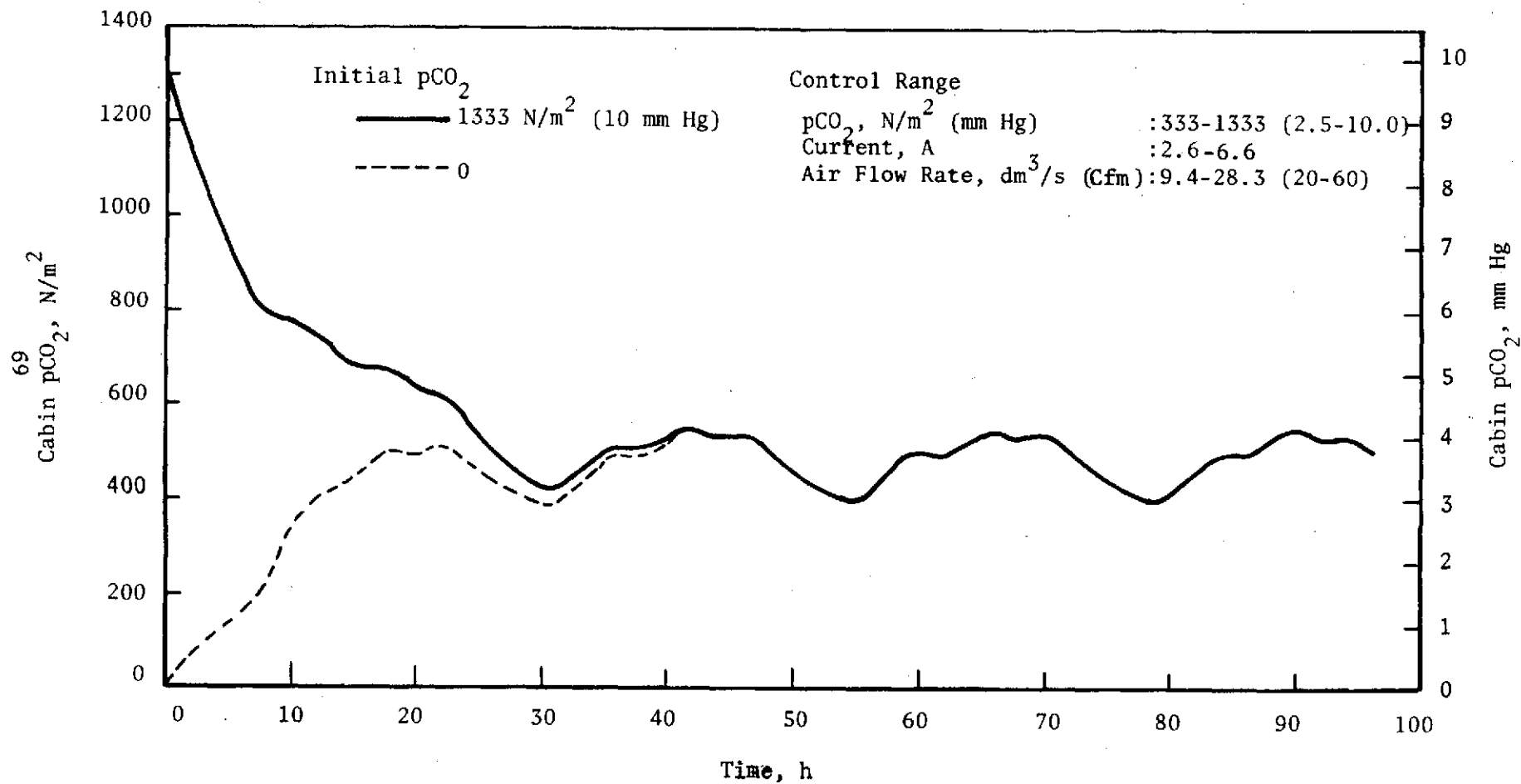


FIGURE 28 CABIN pCO₂ SIMULATION PROFILE FOR CONTROL MODE B(4)

TABLE 11 INPUT VARIABLES FOR SAMPLE MODE B PROBLEMS

Cabin Atmosphere		
Total Pressure, P \emptyset PSA	14.7 Psia	
pCO ₂ , PC \emptyset	0.001, 10 mm Hg	
pO ₂ , PO \emptyset PSA	3.1 Psia	
Temperature, T \emptyset	70F	
Volume, VOLUME	8000 Ft ³	
Process Air Outlet		
Total Pressure, P8PSA	14.75 Psia	
Process Air Inlet		
Temperature, T7	55F	
Flow Rate, V7	265 Scfm ^(a)	
Dew Point Temperature, DW7	50F	
Anode H ₂ /CO ₂ Outlet		
Total Pressure, P4PSA	20 Psia	
System H ₂ Inlet		
Temperature, T9	72F	
Flow Rate, V9SL	10 Scfm ^(a)	
Dew Point Temperature, DW9	69F	
Modules		
Number in Circuit, N	96	
Current, I	N/A ^(b)	
DELTI ^(c)	22F	
Cathode Air Flow Rate, V1	N/A	
Penalty Weight Factors		
Power, PWPEN	0.591 Lb/Watt	
Heat Rejection to Ambient, HTPEN	0.128 Lb/Btu/Hr	
Water Vapor Rejection to Ambient, H2OPEN	134 Lb/Lb H ₂ O/Hr	
Oxygen Consumption, OXPEN	1536 Lb/Lb O ₂ /Hr	
Program Control		
KMODE ^(d)	1	
NFLAG ^(e)	1	
Number of Days to be Simulated, DAYS	4 Days ^(f)	
Integration Time Increment, DT	15 Min ^(g)	
Output Table Time Increment, DPRINT	60 Min	

(a) Reference conditions for standard flow units: 70F, 14.7 Psia

(b) N/A = Not Applicable

(c) DELTI = Module temperature - cathode air inlet dew point temperature

(d) KMODE = 0 - Mode A; 1 - Mode B

(e) NFLAG = 0 - Out-of-tolerance moisture conditions do not stop program

1 - Out-of-tolerance moisture conditions do stop program

(f) DT must be chosen so that the length of each time step in the CO₂ generation rate table is a whole multiple of DT

(g) DPRINT must be a whole multiple of DT

In control Mode A, subsystem equivalent weight and O_2 consumption remain constant. In control Mode B, however, these two parameters vary with time. The steady-state daily equivalent weight and O_2 consumption profiles for the four control Mode B runs are presented in Figures 29 through 36. Subsystem power consumption profiles and any other subsystem performance variable profiles can likewise be predicted, depending upon the specific interests of the program user. In this manner, control Mode A and control Mode B can then be compared on the basis of the important performance parameters for a given application.

CONCLUSIONS

The following conclusions were reached as a direct result of the math model development effort:

1. The CS-6 Base Program developed accurately predicts the performance characteristics of the CS-6 as a subsystem over its typical range in operating conditions.
2. The Cabin pCO_2 Simulation Program developed predicts cabin pCO_2 as a function of a given CO_2 generation profile and spacecraft cabin volume for the CS-6 as the CCS.
3. The Cabin pCO_2 Simulation Program provides a tool for the system designer for use in trade studies to determine subsystem equivalent weight, O_2 consumption, power consumption, and cabin pCO_2 as a function of a CO_2 generation profile for both control Mode A and control Mode B.
4. The CS-6 Base Program and Cabin pCO_2 Simulation Program can be upgraded for use as a hardware design tool. Hardware limitations such as cooling air damper leakage and blower capacity could be eliminated from the program. The result of the upgrading would be a hardware design tool specifically aimed at sizing and designing an EDC CO_2 removal subsystem for general spacecraft application.
5. The experimental work completed provided the necessary data to model the performance of the CS-6 and to verify the model's predictability.

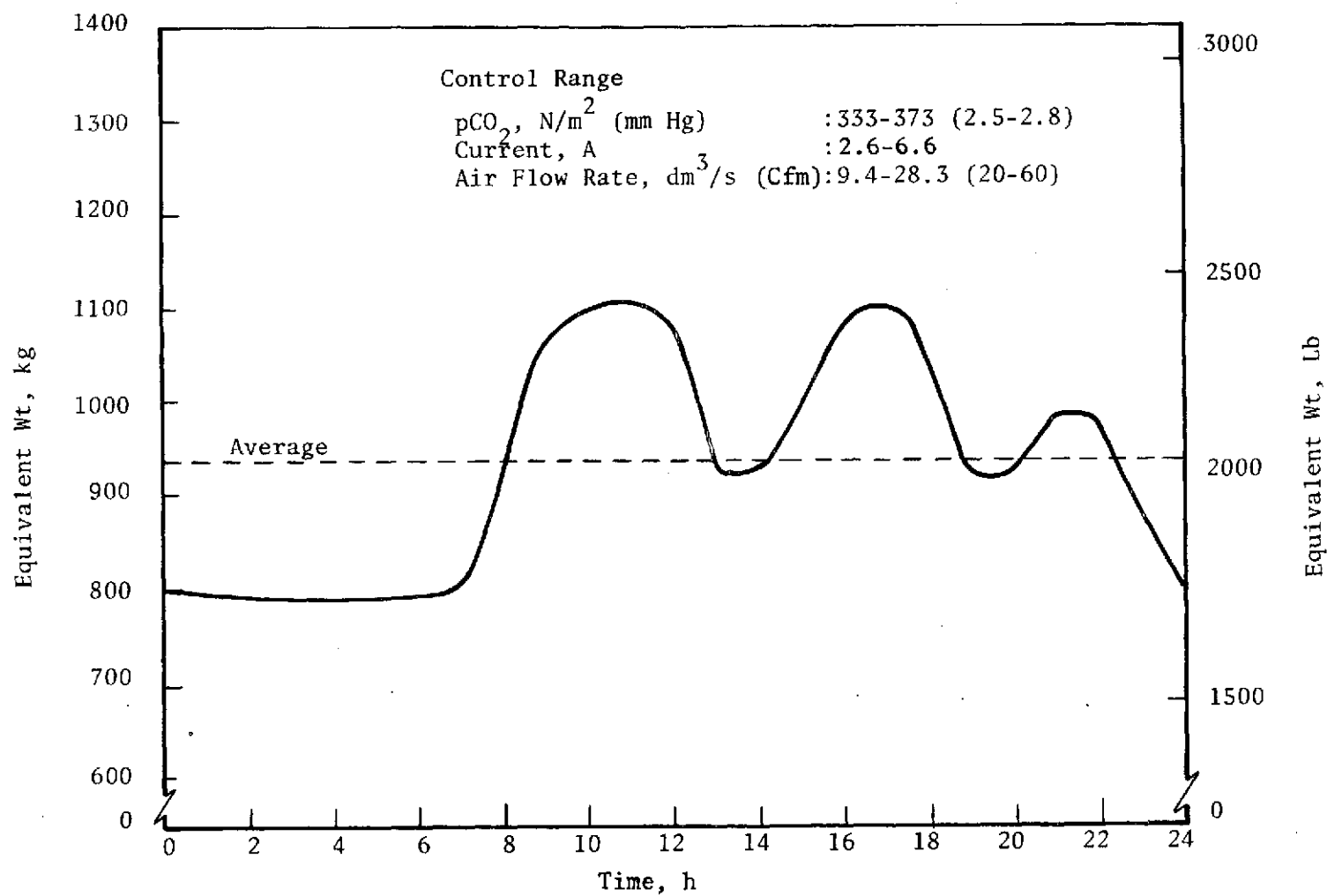


FIGURE 29 STEADY-STATE DAILY EQUIVALENT WEIGHT PROFILE FOR CONTROL MODE B(1)

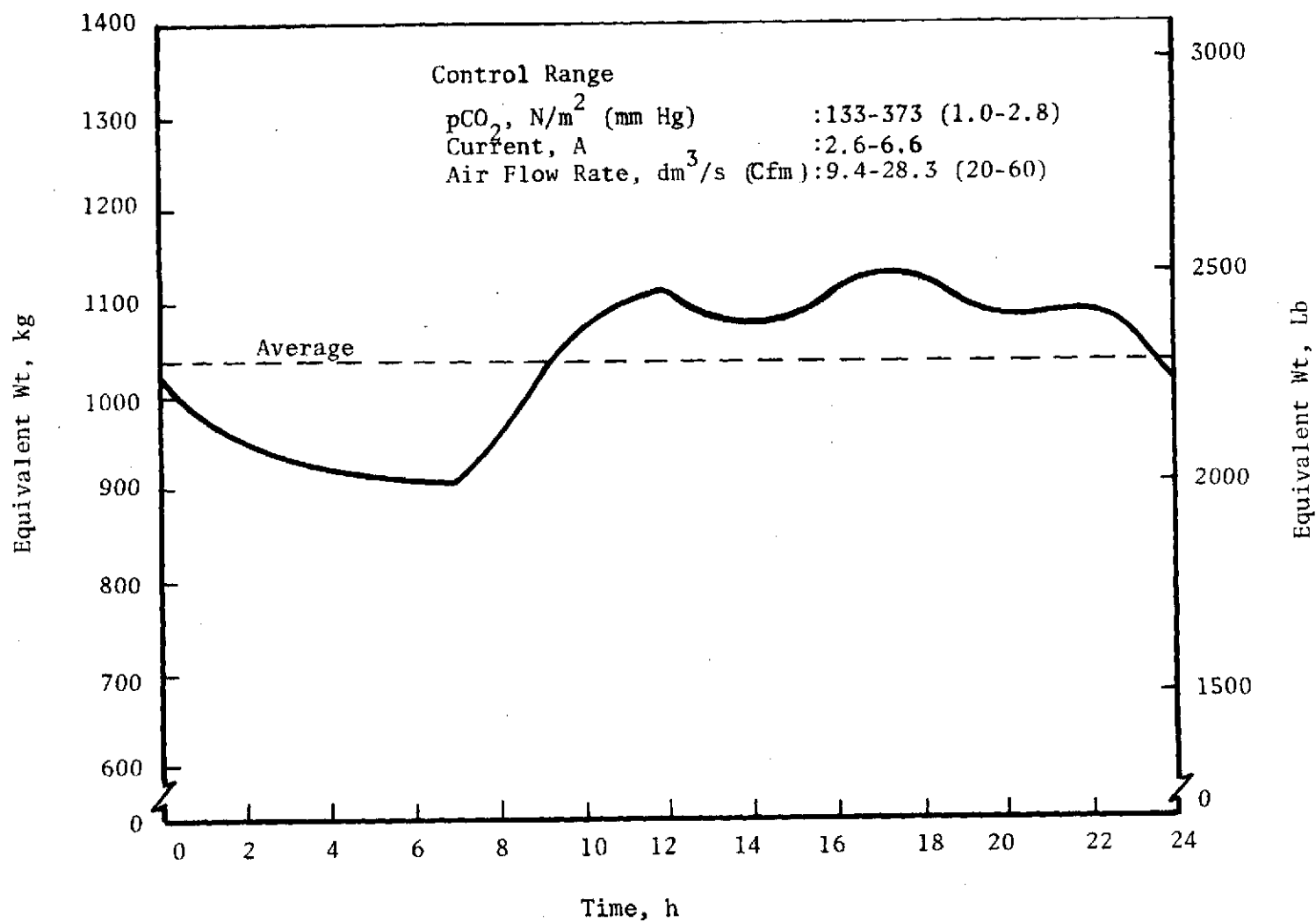


FIGURE 30 STEADY-STATE DAILY EQUIVALENT WEIGHT PROFILE FOR CONTROL MODE B(2)

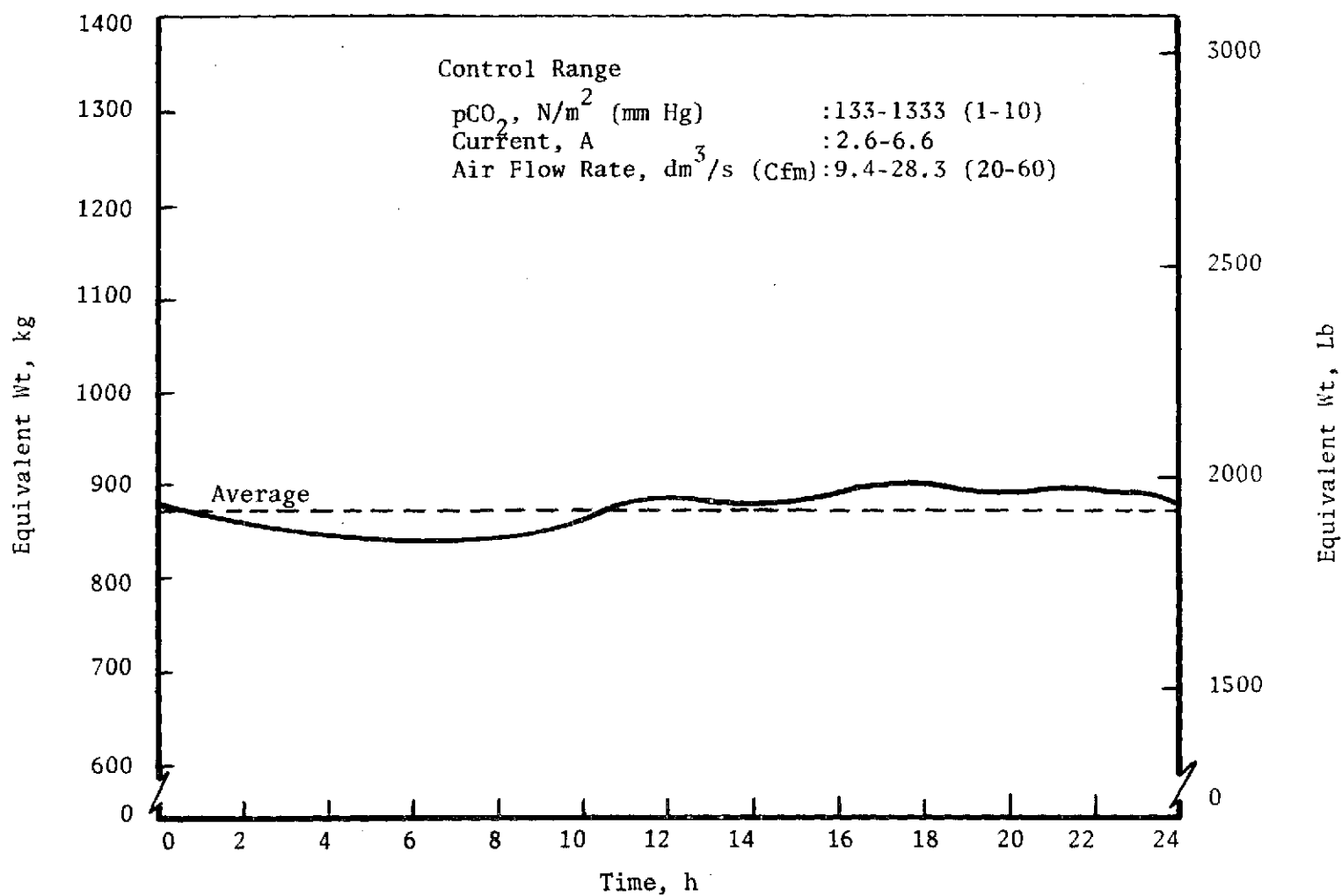


FIGURE 31 STEADY-STATE DAILY EQUIVALENT WEIGHT PROFILE FOR CONTROL MODE B(3)

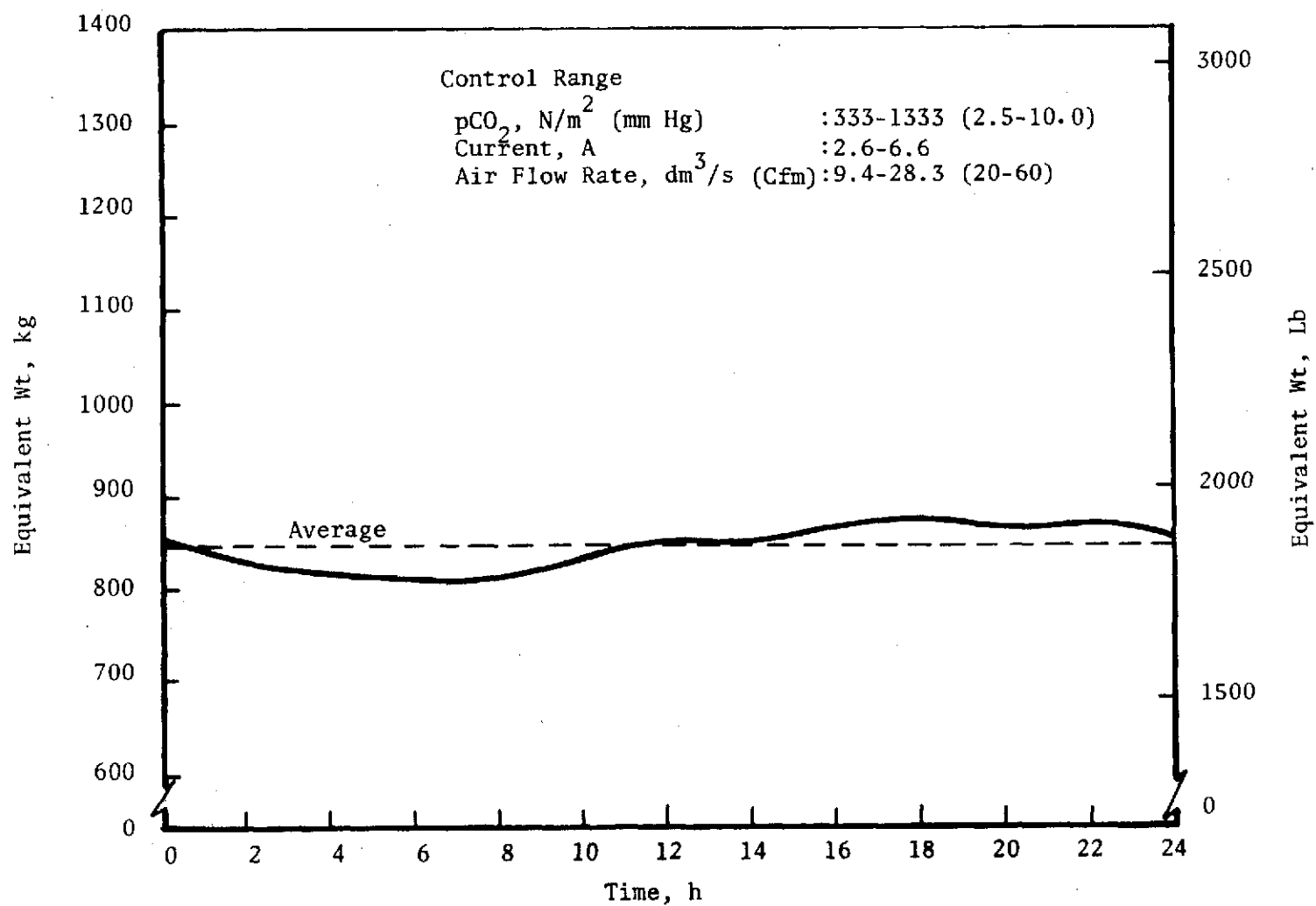


FIGURE 32 STEADY-STATE DAILY EQUIVALENT WEIGHT PROFILE FOR CONTROL MODE B(4)

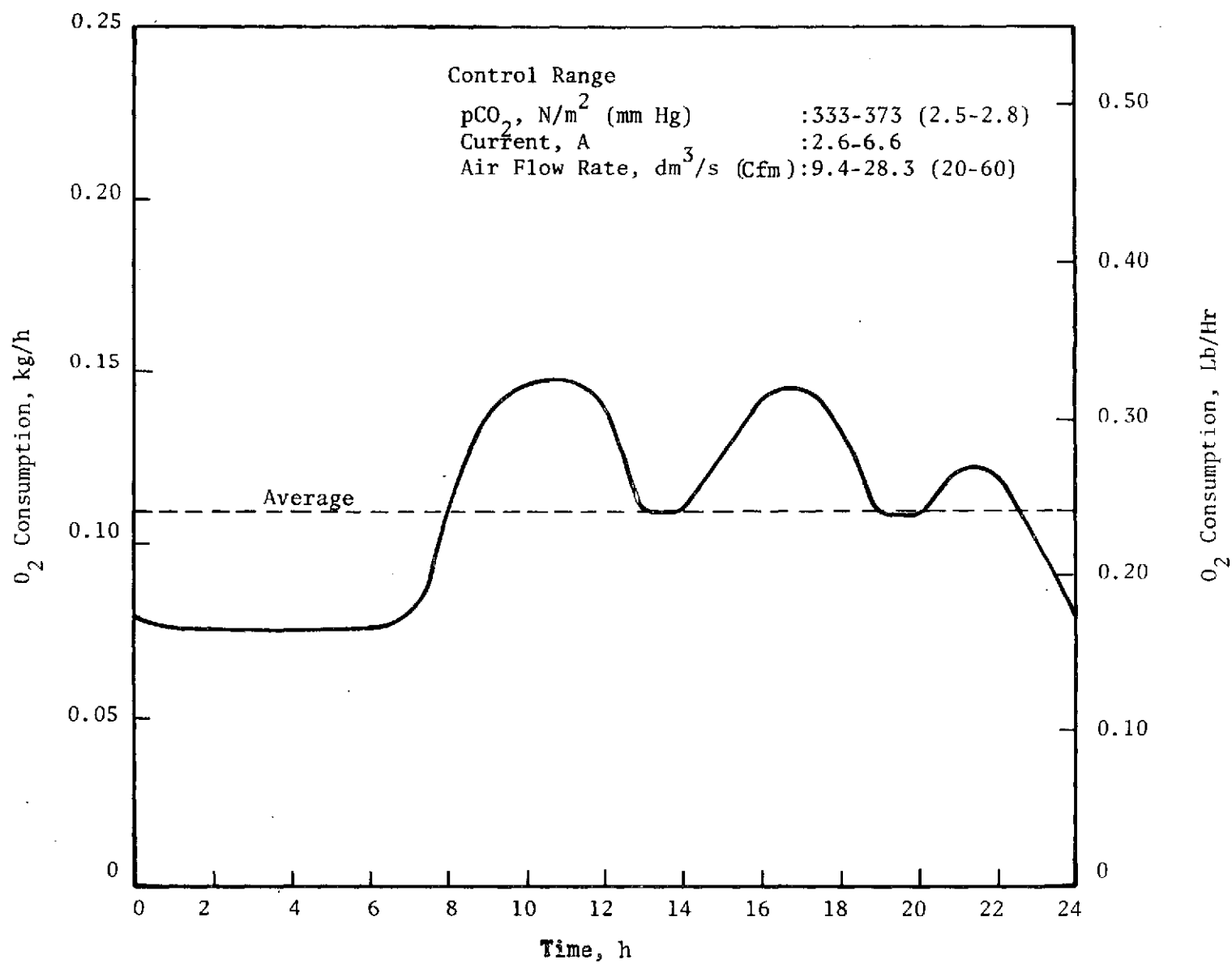


FIGURE 33 STEADY-STATE DAILY O_2 CONSUMPTION PROFILE FOR CONTROL MODE B(1)

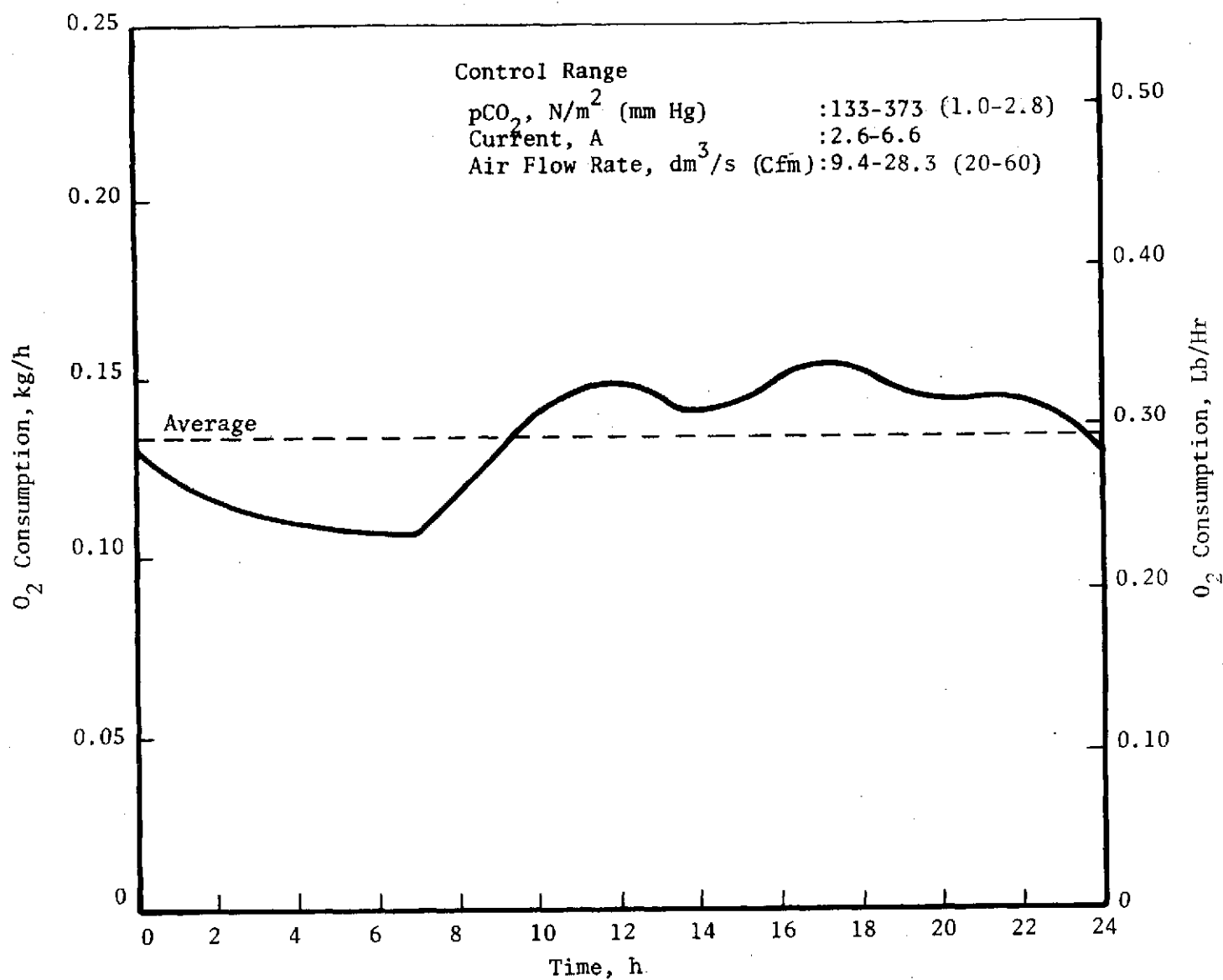
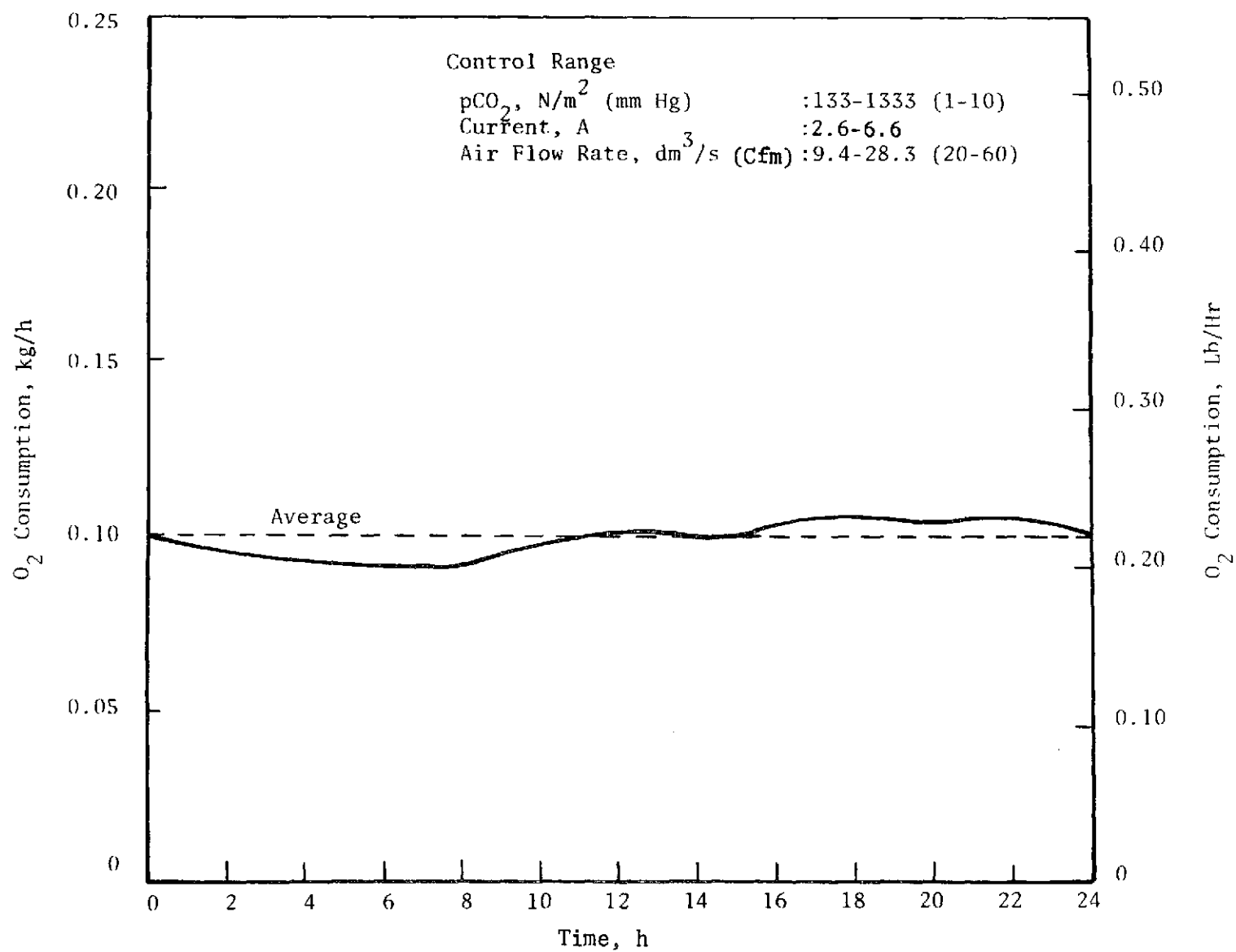
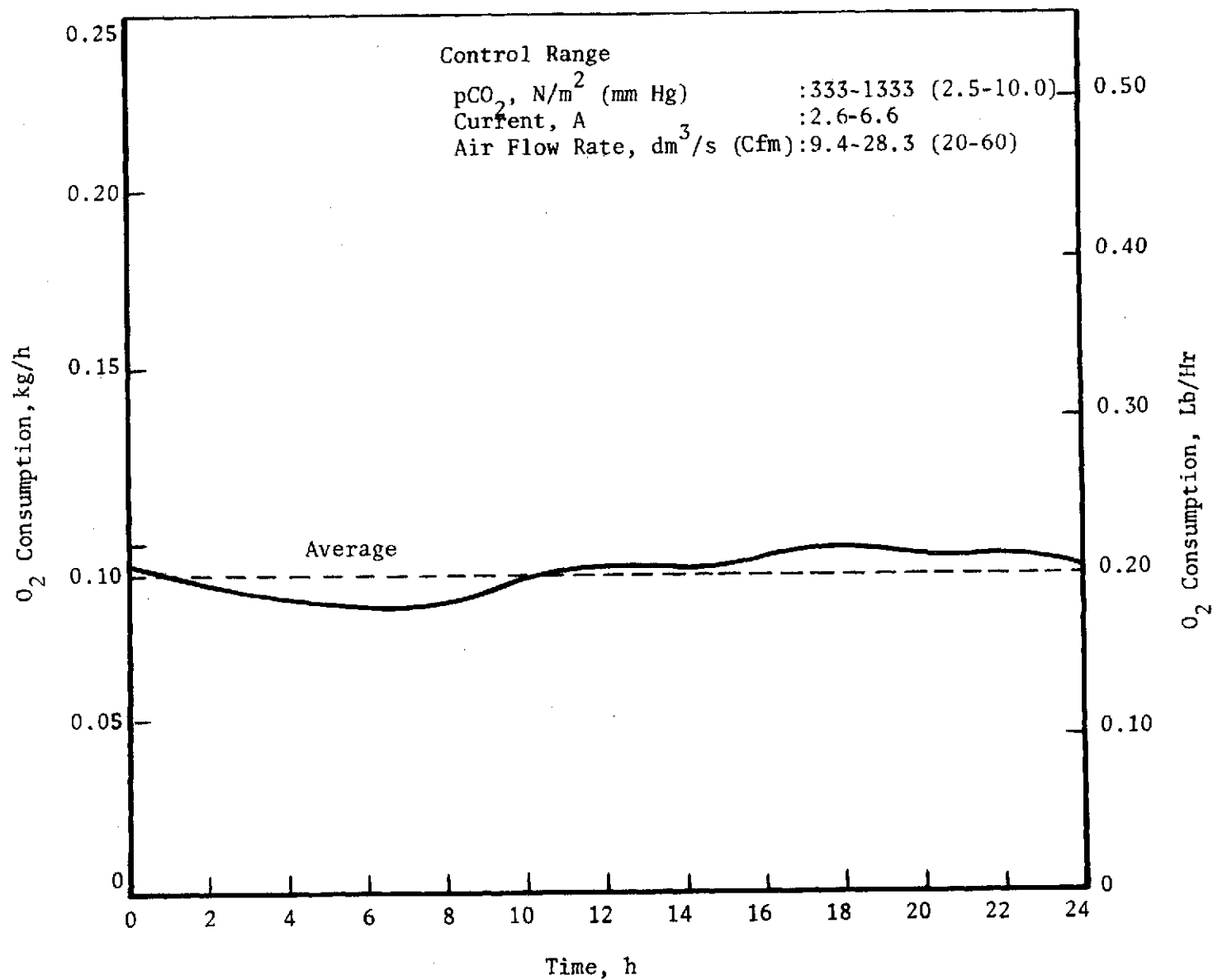


FIGURE 34 STEADY-STATE DAILY O₂ CONSUMPTION PROFILE FOR CONTROL MODE B(2)

FIGURE 35 STEADY-STATE DAILY O₂ CONSUMPTION PROFILE FOR CONTROL MODE B(3)

FIGURE 36 STEADY-STATE DAILY O₂ CONSUMPTION PROFILE FOR CONTROL MODE B(4)


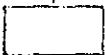

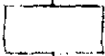
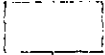

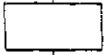


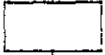



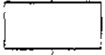
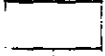
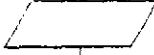

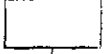

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2. Kostell, G. D., Schubert, F. H., Shumar, J. W., Hallick, T. M. and Jensen, F. C., "Six-Man, Self-Contained Carbon Dioxide Concentrator Subsystem for Space Station Prototype (SSP) Application," Final Report, ER-170-34, NASA CR 114742, Contract NAS2-6478, Life Systems, Inc., Cleveland, Ohio, May, 1974.
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4. Shubert, F. H. and Quattrone, P. D., "Development of a Six-Man, Self-Contained Carbon Dioxide Collection Subsystem for Spacecraft Application," ASME Publication 74-ENAS-16, presented at the Inter-society Conference on Environmental Systems, Seattle, Washington, July 29-August 1, 1974.
5. Schubert, F. H. and Schneider, J. J., "Six-Man, Self-Contained CO₂ Concentrator Extension: New Technology Tasks," First Quarterly Report, ER-170E-2a, Contract NAS2-6478, Life Systems, Inc., Cleveland, Ohio, December, 1973.
6. Bird, R. Byron, Stewart, Warren E. and Lightfoot, Edwin N., "Transport Phenomena," John Wiley & Sons, Inc., New York, 1960.
7. Welty, James R., Wicks, Charles E. and Wilson, Robert E., "Fundamentals of Momentum, Heat and Mass Transfer," John Wiley & Sons, Inc., New York, 1969.

APPENDIX A CS-6 BASE PROGRAM DOCUMENTATION

<u>TABLE</u>		<u>PAGE</u>
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9	Range Test Subroutine	A-29
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11	Checks and Messages	A-42
12	Nomenclature and Units	A-44





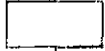


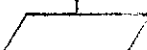







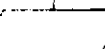
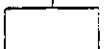

TABLE 1 MAIN PROGRAM FLOW CHART

Symbol	Program Line Numbers	Description	Comments
		START	
	190	CPA = 1.0765	Initialize Constant Btu/Hr/Scfm-F
	190	CPH = 1.0666	Initialize Constant Btu/Hr/Scfm-F
	200	U1 = 51.7	Initialize Constant mm Hg/Psi
	200	U2 = 386.7	Initialize Constant Scfm/Lb-Mol/Hr
	200	U3 = 3.419	Initialize Constant Btu/Hr/Watt
	200	U4 = 28.32	Initialize Constant 1/Ft ³
	210	C782 = 2.25×10^{-5}	Initialize Constants For Pressure Drop Equations
	210	C562 = 1.303×10^{-5}	
	210	C561 = 1.01×10^{-2}	
	210	C6132 = 8.611×10^{-4}	
	220	C5132 = C562 + C6132	
	230	C5131 = C561	
	240	QA = C5132 - C782	
	250	IOUT = 1	Initialize output file device code
	260	PRINT, "FILE INPUT (T OR F)"	
	270	READ, QFIN	
	280	INP = 50	
			

A-2

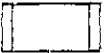
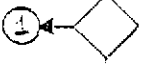

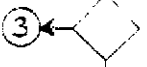



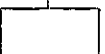
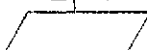
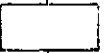
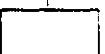
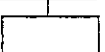
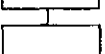

-continued-

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	290	IF (QFIN) INP=2	Open input file if desired
	300	IF (QFIN) OPEN INPUT FILE	
	310	PRINT, "FILE OUTPUT (T OR F)"	Should output be written into a file? If not, correct the output device code for direct terminal output.
	320	READ, QFOUT	
	330	IF (NOT QFOUT) IOUT = 66	
			
	360	IF (NOT QFOUT) BRANCH	If file output was used, read in the file name. If the file is completed, close it and assign the name to it.
	370	IF (NOT QFIN) PRINT, "FILE FOR OUTPUT"	
	380-390	READ (INP, 48) FNAME	
	400	IF (FNAME = "WAIT") BRANCH	
	410-430	END, CLOSE AND REWIND FILE	
			
			Read in and write out input variables
	450-470	READ: POPSA, PCO, POOPSA, P8PSA, T7, V7, DW7, P4PSA, T9, V9SL, DW9, N, I, DELT1, V1, PWPEN, HTPEN, H2OPEN, OXPEN, NFLAG	
	510-750	WRITE INPUT VARIABLES	
	790	IR=0	Initialize out of range input variable counter
	800	CALL T ("POPSA," POPSA, 13.7, 15.7, IR)	Subroutine T checks each input variable against its allowable range. Out of range variables are printed and cause IR to be incremented.
	810-990		

A-3

Table 1 - continued






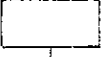
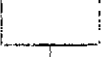
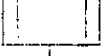

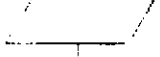




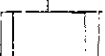
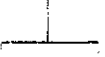


Symbol	Program Line Numbers	Description	Comments
	1000	CALL T ("NFLAG,", FLAG, 0, 1, IR)	
	1010	IF (IR > 0) BRANCH	If the counter shows that one or more input variables is out-of-range, abort the simulation and read in next set of data.
	1050	$V9MSL = (1.3)(N)(I)(7.058 \times 10^{-3})$	Calc. required H ₂ flow
	1060	IF V9MSL < V9SL THEN BRANCH	Check for sufficient H ₂ Flow
	1070-1080	WRITE "INSUFFICIENT H ₂ ," V9MSL, "IS REQUIRED"	Write error message and required H ₂ flow Return for new inputs
			
	1140	IF V1 ≤ 70 THEN BRANCH	Check that V1 is less than the process air blower capacity
	1150	V1 = 70	Set V1 to maximum blower capacity
	1160-1180	WRITE "AIRFLOW CHANGE TO 70 SCFM"	Print error message
	1220	$V7M1 = V7 - V1$	Calculate bypass cooling air flow with cooling blowers off; i.e., calculate minimum cooling air flow rate
	1230	$QB = C5131 + 2(V7M1)^2$	
	1240	$QC = C782 (V7M1)^2$	
	1250	$V5MIN = \frac{-QB + QB^2 + 4(QA)(QC)}{2(QA)}$	
	1290	DW1 = DW7	

A-4

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
A-5	1300	$T2 = DW1 + DELT1$	Calculate cell temperature
	1310	$T2INP = T2$	Store input T2
	1320	$E = 0.729 - 0.22 \ln I + 0.008I + 0.005 (T2-78)$	Calculate cell voltage
	1330	$HEATLD = (1.25-E) (N) (I) (U3)$	Calculate modules' heatload
	1340	$T1 = T7$	
	1350	$T3 = T9$	
	1360	$V3 = V9SL/U4$	
	1370	$T5 = T1$	
	1380	$DHA = V1 (CPA) (T2 - T1)$	Calculate heat removed by cathode air flow
	1390	$DHH = V3 (CPH) (T2-T3)$	Calculate heat removed by H_2
S-5	1400	$DHC = HEATLD-DHA-DHC$	Calculate heat removed by cooling air
	1440	If $DHC > 0$ THEN BRANCH	Check to see if cooling air is required
	1490	$V5 = V5MIN$	Set cooling air flow to minimum
	1500	$V5A = (N) (V5MIN)/96$	Calculate flow thru active cells
	1510	CALL TDRIFT	Calculate T2 for subcooled condition

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	1520	$DROP = T2INP - T2$	Calculate temperature, T2, drop
	1530-1560	WRITE "V5MIN," V5MIN "COOLING BLOWERS OFF," "MODULE TEMPERATURE FALLS," DROP, "NEW T2," T2	Print out new conditions
			
			
	1630	IF $T2 - T5 \geq \frac{(0.376)DHC}{N}$ THEN BRANCH	Check if there is sufficient ΔT to conduct heat up fins
	1680	$V5 = 440$	Set V5 to maximum blower capacity
	1690	$V5A = V5(N)/96$	Calculate flow thru active cells
	1700	Call TDRIFT	Calculate T2
	1710	$RISE = T2 - T2INP$	Call rise in module temperature
	1720-1740	WRITE "COOLING BLOWERS ON FULL," "MODULE TEMPERATURE RISES," RISE, "NEW T2," T2	Print out new conditions
			
			
	1800	$VA = 1.01 \times DHC/CPA (N) (T2 - T5)$	Calculate minimum and maximum cooling air flow to set range for iterative subroutine "ROOT"
	1810	$VB = 2(VA)$	
	1820	$V5A = (N) \cdot \text{ROOT}(VA, VB, ERT, 0, 0.005, 0.001, 20)$	Calculate cooling air flow past active cell
	1830	$V5 = 96(V5A)/N$	Calculate total cooling air flow
	1880	If $V5 < V5MIN$ THEN BRANCH	Check for subcooling
			

A-6

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
⑧	1890	If V5 > 440 THEN BRANCH	Check for heatup
	1900-1920	WRITE "COOLING BLOWERS IN RANGE"	Print clarifying statement
⑥	1970	V10 = V7-V1-V5	Calculate plenum bypass flow
	2020	IF V10 ≥ 0.005 (V8) THEN BRANCH	Check for sufficient plenum bypass
	2030-2060	WRITE "INSUFFICIENT AIR FLOW, RECIRCULATION OF AIR FROM OUTLET TO INLET"	Print error message
①	2120	$COR34 = \frac{(14.1)^{0.8}}{P4PSA}$	Calculate module H ₂ cavity pressure drop
	2130	P4 = P4PSA (V1)	
	2140	V3SL = V9SL	
	2150	DP34 = (0.3822) (COR34) (V3SL)	
	2150	IF V3SL ≤ 22 THEN BRANCH	Calculate module H ₂ inlet pressure
	2150	$DP\ 34 = COR34 (8.3183^{+1.75} 0.4187 (V3SL-21.5801)^{1.75})$	
	2170	P3 = P4 + DP34	
	2180	P3PSA = P3/U1	
	2190	$COR93 = \frac{(14.1)^{0.8}}{P3PSA}$	Calculate H ₂ distribution block pressure drop
	2200	DP93 = (COR93) (10.64) (V3SL)	

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	2210	IF V3SL \leq 6.2 THEN BRANCH	
	2210	DP93 = COR93 [35.64 V3SL - 195.25 + e ^(7.75-0.6537V3SL)]	
	2220	P9 = P3 + DP93	Calculate H ₂ inlet pressure
	2230	P9PSA = P9/U1	
	2240	DP78 = 2.25 x 10 ⁻⁵ (V10) ²	Calculate process air inlet pressure using plenum pressure drop correlation
	2250	P8 = P8PSA(U1)	
	2260	P7 = P8 + DP78	
	2270	P7PSA = P7/U1	
	2280	DP12 = 0.001903(V1) ² + 0.04877(V1)	Calculate cathode air pressure drop
	2290	P1 = P7	
	2300	P2 = P1-DP12	Calculate cathode air out pressure
	2310	PC1 = PCO $\frac{P7PSA}{POPSA}$	Calculate cathode inlet pCO ₂
	2320	CURDEN = I/0.244	Calculate current density
	2330	DELT1E = T2-DW1	Calculate actual humidity ΔT
	2340	TI = TICOR (PC1, V1/96, CURDEN, DELT1E)	Calculate TI
	2350	OCON = 6.5803 x 10 ⁻⁴ (N) (I)	Calculate O ₂ consumed

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	2360	CTrans = TI (OCON)	Calculate CO ₂ transferred
	2370	HCON = OCON $\frac{2.016}{16}$	Calculate H ₂ consumed
	2380	WPROD = HCON + OCON	Calculate water produced
	2390	VC4 = CTRANS $\frac{V2}{44.01 \times 60}$	
	2400	PW9 = PHTO (DW9)	
	2410	PW3 = P3 $\frac{PW9}{P9}$	Calculate anode gas stream parameters
	2420	VH3 = V3 $(1 - \frac{PW3}{P3})$	
	2430	VH4 = VH3 - HCON $\frac{U2}{2.016 \times 60}$	
	2450	PW4 = PHTO (T2-6)	
	2460	VW4 = $\frac{PW4}{P4 - PW4}$ (VC4 + VH4)	
	2470	DW1 = DW7	
	2480	PW1 = PHTO (DW1)	Calculate cathode air water balance parameters
	2490	VW1 = V1 $\frac{PW1}{P1}$	
	2500	VW3 = V3 - VH3	
	2510	VWPROD = WPROD $\frac{V2}{18.01 \times 60}$	
	2520	VW2 = VW1 + VW3 - VW4	
	2530	POO = POOPSA/U1	
	2540	PO7 = POO (P7/PO)	

6-A

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
A-10	2550	$PO1 = PO7$	Calculate cathode air inlet stream parameters
	2560	$PN1 = P1 - PO1 - PW1 - PC1$	
	2570	$VN1 = V1 (PN1/P1)$	
	2580	$VO1 = V1 (PO1/P1)$	
	2590	$VC1 = V1 (PC1/P1)$	
	2600	$VN2 = VN1$	Calculate cathode air outlet stream parameters
	2610	$VO2 = VO1 - OCON (U2/32 \times 60)$	
	2620	$VC2 = VC1 - VC4$	
	2630	$V2 = VO2 + VN2 + VW2 + VC2$	
	2640	$PW2 = \frac{VW2}{V2} P2$	
	2650	$DW2 = DEWT (PW2)$	
	2710	IF $T1-DW1 = 11.25 \pm 1.75$ AND $T2-DW2 = 11.25 \pm 1.75$ THEN BRANCH	
A-11	2720	IF $T1-DW1 \geq 4$ THEN BRANCH	
	2850-2860	WRITE "INLET AIR HUMIDITY OUT-OF-RANGE"	
	2730	IF $T1-DW1 \leq 14$ THEN BRANCH	

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	2740	IF T2-DW2 \geq 7 THEN BRANCH	Perform moisture balance checks
	2880-2890	WRITE "OUTLET AIR HUMIDITY OUT-OF-RANGE"	
	2750	IF T2-DW2 \leq 19 THEN BRANCH	
	2760	DPTDAV = $\frac{1}{2}$ (T1-DW1+T2-DW2)	
	2770	IF DPTDAV = 11 \pm 1.5 AND EITHER T2-DW2 \geq 13 OR DPTDAV \geq 0 THEN BRANCH	
	2780-2790	WRITE "AVE DEW PT DEPRESSION OUT-OF-RANGE"	Check NFLAG for program abort
	2800-2820	WRITE "ELECTROLYTE MOISTURE BALANCE NOT MAINTAINED"	
	2830	IF NFLAG = 1 THEN BRANCH	
	2950	DELT1P = 22-T1 + DW2	
	2960	T2P = DP1 + DELT1P	
	2970	PW7 = PW1	Calculate preferred ΔT
	2980	PN7 = PN1	
	2990	PC7 = PC1	
	3000	VC7 = $\frac{PC7}{P7}$ (V7)	
	3010	VW7 = $\frac{PW7}{P7}$ (V7)	
			Complete definition of process air inlet stream

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	3020	$PO7 = PO1$	
	3030	$VO7 = \frac{PO7}{P7} (V7)$	
	3040	$VN7 = \frac{PN7}{P7} (V7)$	
	3050	$RH7 = 100 \left(\frac{PW7}{PHTO(T7)} \right)$	
	3060	$FC1 = VC1 \left(\frac{44.01 \times 60}{U2} \right)$	Complete cathode air inlet stream definition
	3070	$FW1 = VW1 \left(\frac{18.01 \times 60}{U2} \right)$	
	3080	$RH1 = RH7$	Complete cathode air inlet def.
	3090	$PH3 = P3 - PW3$	Complete definition of H_2 inlet
	3100	$FH3 = VH3 \left(\frac{2.016 \times 60}{U2} \right)$	
	3110	$EMOD = 16 (E)$	Calculate remaining module parameters
	3120	$POWER = (N) (I) (E)$	
	3130	$TE = TI/0.0275$	
	3140	$PC2 = VC2 \left(\frac{P2}{V2} \right)$	Complete definition of cathode air outlet
	3150	$FC2 = FC1 - CTRANS$	
	3160	$FW2 = VW2 \left(\frac{18.01 \times 60}{U2} \right)$	
	3170	$RH2 = 100 \left(\frac{PW2}{PHTO(T2)} \right)$	
	3180	$T4 = T2$	

Table 1 - continued

<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
	3190	$V9 = V3$	
	3200	$DW4 = 0.77 \left(\frac{DW1 + DW2}{2} \right) + 0.23T2$	Refined H_2 dew point correlation
	3210	$PW4 = PHTO(DW4)$	Complete definition of anode gas outlet
	3220	$VW4 = \frac{PW4}{P4 - PW4} (VH4 + VC4)$	
	3230	$V4 = VH4 + VC4 + VW4$	
	3240	$V4SL = V4(U4)$	
	3250	$VC4SL = VC4(U4)$	
	3260	$VH4SL = VH4(U4)$	Complete definition of anode gas outlet
	3270	$FC4 = CTRANS$	
	3280	$FH4 = VH4 \left(\frac{2.016 \times 60}{U2} \right)$	
	3290	$FW4 = VW4 \left(\frac{18.01 \times 60}{U2} \right)$	
	3300	$F4 = FC4 + FH4 + FW4$	
	3310	$CHWRTO = FC4/FH4$	
	3320	$HCVRTO = VHR/VC4$	
	3330	$P5 = P7$	
	3340	$DP56 = (V5)^2 C562 + V5(C561)$	Calculate cooling air pressure drop
	3350	$P6 = P5 - DP56$	Calculate cooling air outlet pressure
	3360	$T6 = \frac{(V5A)T6A + (V5 - V5A)T5}{V5}$	Calculate cooling air out temperature

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	3370	IF $V1 \leq 62$ THEN $PWRCTB = 2.8V + 153.8$	Calculate cathode air blower power
	3380	IF $62 < V1 \leq 65$ THEN $PWRCTB = 40V1 - 2150$	
	3390	IF $65 < V1 \leq 70$ THEN $PWRCTB = -34V + 2660$	
	3400	$T11 = T2 + \frac{PWRCTB(U3)}{V1 \cdot CPA}$	Define stream after cathode blower
	3410	$V11 = V2$	
	3420	$P11 = P8$	
	3430-3450	IF $V5 - V5MIN < 0.001(V5MIN)$ THEN $PWRCLB = 0$, $DP1213 = C12132(V5)^2$ AND BRANCH	Check if cooling blower is off
	3460	$DP1213 = C12132 (V5MIN)^2$	
	3470	$TR = \left(\frac{DP78}{1.869} + 0.05 \right) / 1.3$	
	3480	$TR = TR^{(0.128 + 0.102(\frac{DP78}{1.869}))}$	Calculate cooling blower power
	3490	$PWH = 410 - 0.00396 (V5 - 368)^2$	
	3500	$PWL = 410 - 0.00178 (V5 - 306)^2$	
	3510	$PWRCLB = TR (PWH) + (1 - TR) (PWL)$	Define cooling blower exit stream
	3530	$P12 = P8 + DP1213$	
	3540	$+12 = T6 + \frac{PWRCTB(U3)}{V5 (CPA)}$	
	3550	$T13 = T12$	

A-14

Table 1 - continued

<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
A-15	3560	$V12 = V5$	
	3570	$P13 = P8$	
	3580	$V13 = V5$	
	3590	$V8 = V10 + V2 + V5$	
	3600	$VW8 = VW7 + VW2 - VW1$	
	3610	$VC8 = VC7 - VC4$	
	3620	$PC8 = \left(\frac{VC8}{V8}\right) P8$	Calculate plenum exit conditions
	3630	$VN8 = VN7$	
	3640	$PN8 = \left(\frac{VN8}{V8}\right) P8$	
	3650	$VO8 = VO7 - \frac{1}{2}(VH3 - VH4)$	
	3660	$PW8 = \left(\frac{VW8}{V8}\right) P8$	
	3670	$DW8 = DEWT (PW8)$	
	3680	$T8 = \frac{T11(V11) + T13(V13)}{V8} + \frac{T7(V10) + POWER \frac{U3}{CPA}}{V8}$	
	3690	$RH8 = \frac{100 \times PW8}{PHTO (T8)}$	
	3700	$AV7 = \frac{V7(T7 + 460)}{P7} \left(\frac{760}{530}\right)$	

Table 1 - continued

<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
	3710	AV1 = V1 (AV7/V7)	Calculate actual stream flow rates
	3720	AV2 = $\frac{V2(T2 + 460)}{P2} \times 1.434$	
	3730	AV11 = $\frac{V11(T11 + 460)}{P11} (1.434)$	
	3740	AV9 = $\frac{V9(T9 + 460)}{P9} (1.434)$	
	3750	AV3 = $\frac{V3(T3 + 460)}{P3} (1.434)$	
	3760	AV4 = $\frac{V4(T4 + 460)}{P4} (1.434)$	Calculate actual stream flow rates
	3770	AV5 = V5 AV7/V7	
	3780	AV6 = $\frac{V6(T6 + 460)}{P6} (1.434)$	
	3790	V6A = V5A	
	3800	AV6A = $\frac{V6A(T6A + 460)}{P6} (1.434)$	
	3810	AV12 = $\frac{V12(T12 + 460)}{P12} (1.434)$	
	3820	AV13 = $\frac{V13(T13 + 460)}{P13} (1.434)$	
	3830	AV10EX = $\frac{V10(T7 + 460)}{P8} (1.434)$	
	3840	AV8 = $\frac{V8(T8 + 460)}{P8} (1.434)$	Calculate equivalent weight penalty
	3880	HRDWGT = 817.9	
	3890	PWRPC = 136	
	3900	PWREC = 45	
	3910	PWRDAU = 100	

Table 1 - continued


<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
A-17 	3920	$PWRTOT = PWRPC + PWREC + PWRCLE + PWRCTB + PWRDAU$	
	3930	$HTTOT = HEATLD + U3(PWRTOT + POWER)$	
	3940	$PWRWGT = PWPEN(PWRTOT)$	Calculate equivalent weight penalty
	3950	$HTWGT = HTPEN(HTTOT)$	
	3960	$H2OWGT = H2OPEN(WPROD)$	
	3970	$OXWGT = OXPEN(OCON)$	
	3980	$EQWGT = PWRWGT + HTWGT + H_2OWGT + OXWGT + HRDWGT$	
	3990-4710	WRITE OUT ALL OUTPUTS	
		END OF PROGRAM	

TABLE 2 WATER VAPOR PRESSURE FUNCTION

<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
A-18	4750	FUNCTION PHTO(TF)	The input parameter is the Fahrenheit dew point temperature. The output parameter is p_{H_2O} , in millimeters of mercury.
	4760-4770		Initialize constants A-G.
	4780	$TC = (TF - 32) \cdot 1.8$	Calculate Centigrade dew point temperature.
	4790	$X = 374.11 - TC$	Calculate the temperature span from the dew point to the critical temperature.
	4800	$PHTO = 10^{(EE - \frac{X}{TC + F} \times \frac{A + BX + CX^3}{1 + DX})}$	Calculate water vapor pressure
	4810	RETURN	

TABLE 3 DEW POINT TEMPERATURE FUNCTION




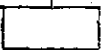
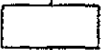

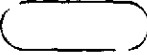











Symbol	Program Line Numbers	Description	Comments
	4840	FUNCTION DEWT(P)	The input parameter P is the water vapor pressure in millimeters of mercury. The output parameter DEWT is the Fahrenheit dew point temperature
	4850	EXTERNAL ROOT, PHTO	Functions ROOT and PHTO are used by function DEWT
	4860	X=ALOG(P)	Calculate two trial values for the dew point temperature
	4870	$TA = -2.4 + 20.25X + 1.522X^2$	
	4880	TB=TA + 0.1	
	4890	DEWT=ROOT(TA,TB,PHTO,P,0.005, 0.005, 5)	Function ROOT will call function PHTO starting with dew points equal to TA and TB until the water vapor pressure is equal to P with temperature and vapor pressure tolerances of point .005 but not exceeding five trials.
	7700	RETURN	

TABLE 4 TRANSFER INDEX FUNCTION

Symbol	Program Line Numbers	Description	Comments
	4930	FUNCTION TICOR(PC,AF,CD,DEL)	Input parameters are CO ₂ partial pressure in millimeters of mercury, cathode air flow in Cfm/cell, current density in Amp/Ft ² , and module temperature - inlet cathode air dew point temperature. The output parameter is TICOR in Lb CO ₂ /Lb O ₂ .
	4940-5010		Initialize the correlation parameters in array S.
	5020	$PA = PC \left(\frac{AF}{.44} \right) (1 + .84P)^{-.84P}$	PA is the effective inlet pCO ₂ corrected for nonbaseline cathode air flow.
	5030	$J = \frac{CD}{5} - 1$	Calculate the J index which corresponds to current density.
	5040	IF (J < 1) J=1	For current densities less than 10 ASF, extrapolate from 15 and 10 ASF.
	5050	$TI1 = \sum_{i=1}^5 S_{ij} PA^i$	Calculate TI at the current density just below the actual current density.
	5060	IF (J < 7) BRANCH	Current density should not exceed 40 ASF.
	5070	TICOR = TI1	
	5090	J = J + 1	Calculate TI at the current density just above the actual current density.
	5100	$TI2 = \sum_{i=1}^5 S_{ij} PA^i$	
	5110	AII=J	Interpolate between the two current densities.

-continued-

Table 4 - continued

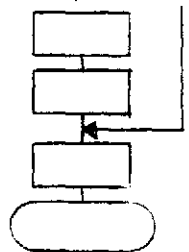
<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
	5120	$TERP = \frac{CD}{5} - AII$	
	5130	$TICOR = TI2 \times TERP + TI1(1 - TERP)$	
	5140	$TICOR = TICOR(1 + .03536(D\bar{E}L - 18.33))$	Correct TI for moisture conditions.
	5050	RETURN	

TABLE 5 ROOT FUNCTION

Symbol	Program Line Numbers	Description	Comments
	5180	FUNCTION ROOT(X1,X2,YFCN,W,XTOL, YTOL,K)	Input parameters are the first and second trial root values, the function to be called which returns the function of X, the value of the function at the desired root, X tolerance, Y tolerance, and maximum trials. The output value, ROOT, is the value of X when the function equals W.
	5190-5200		Initialize common and external statements.
	5210	XA=X1	Isolate X1 and X2.
	5220	XB=X2	
	5230	FA=YCFN(XA) - W	Find the error values at XA and XB.
	5240	FB=YCFN(XB) - W	
	5250	BEGIN LOOP	
	5260	$XN = \frac{FA \cdot XB - FB \cdot XA}{FA - FB}$	Extrapolate from the previous two trial values.
	5270	FN=YFCN(XN) - W	Calculate the error at the next X value.
	5280-5290	IF(FN < YTOL and XN-XB < XTOL) BRANCH	BRANCH when the X and Y values are within tolerance.
	5300-5320	IF(Kth TIME THRU LOOP) DUMP VARIABLES & PRINT MESSAGE "NONCONVERGENCE IN LOOP"	If the root has not been found within K trials, print a message.
	5330	XA=XB	Drop the oldest trial value and add the new trial value.

-continued-

Table 5 - continued


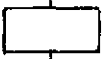


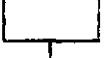
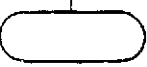
<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
	5340	XB=XN	
	5350	FA=FB	
	5360	FB=FN	
	5370	IF(<Kth TIME THRU LOOP)BRANCH	
	5380	ROOT = XN	The root of the function returned is the latest trial value.
	5390	RETURN	

TABLE 6 MODULE TEMPERATURE SUBROUTINE

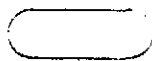
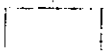
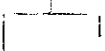
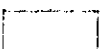

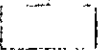



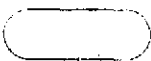
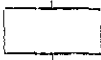
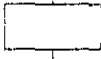
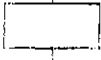
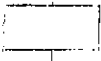

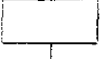

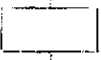
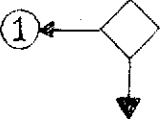
<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
	5420	SUBROUTINE TDRIFT	Subroutine TDRIFT calculates the module temperature when the cooling air flow rate is specified. All inputs are through common storage. All outputs except P2 are also through common storage.
	5430-5460		Initialize type, common, and external statements.
	5470	$ENTHPR = V1 \cdot CPA \cdot T1 + V3 \cdot CPH \cdot T3$	Calculate enthalpy entering the modules in the cathode air and inlet hydrogen streams.
	5480	$T2HIGH = \frac{ENTHPR + .99 \cdot HEATLD}{V1 \cdot CPA + V3 \cdot CPH}$	Calculate maximum possible module temperature. This is the temperature the module would rise to with no cooling air.
	5490	$T2LOW = \frac{ENTHPR + V5A \cdot CPA \cdot T5 + HEATLD}{V1 \cdot CPA + V3 \cdot CPA + V5A \cdot CPA}$	Calculate the minimum module temperature which would occur with no heat transfer resistance.
	5500	$T2 = T2HIGH$	Call subroutine ERT to determine values of the heat transfer coefficient and the cooling fin efficiency, neither of which depends upon module temperature but only upon cooling air flow rate which is constant when subroutine TDRIFT is called.
	5510	$DUMMY = ERT(V5A/N)$	
	5520	$T2 = \text{ROOT}(T2HIGH, T2LOW, ERT1, 0, 0.005, 0.005, 0.20)$	Start with trial values T2HIGH and T2LOW and use function ERT1 to find the module temperature which yields a heat balance for the specified cooling air flow rate.
	5530	RETURN	

TABLE 7. HEAT BALANCE FUNCTION WITH VARIABLE MODULE TEMPERATURE

Symbol	Program Line Numbers	Description	Comments
	5560	FUNCTION ERT1(T)	The input parameter is the module temperature. The output parameter, ERT1, is the difference between the available module cooling air temperature drop and the required module cooling air temperature drop.
	5570-5590		Initialize type, common statements.
	5600	$E = 0.729 - 0.221nI + 0.0081 + 0.005(T-78)$	Calculate module voltage and heat load at the given temperature.
	5610	$HEATLD = N \cdot I \cdot (1.25 - E) \cdot 3.419$	
	5620	$DHA = V1(CPA)(T - T1)$	Calculate the enthalpy change for the cathode air process hydrogen and cooling air flow, respectively, at the given module temperature.
	5630	$DHH = V3(CPH)(T - T3)$	
	5640	$DHC = HEATLD - DHA - DHH$	
	5650	$T6A = T5 + \frac{DHC}{V5A(CPA)}$	Calculate the outlet cooling air temperature from the inlet cooling air temperature and the enthalpy increase.
	5660	$DTREQ = DHC \left(0.376 + 3.876 \frac{HC \cdot ETA}{N} \right)$	The required module cooling air temperature difference depends upon the cooling air enthalpy change x the resistance in the fin roots + the gas film resistance.
	5670	IF (T6A < T) BRANCH	If the cooling air temperature at the exit is less than the module temperature, then the log mean temperature difference can be calculated.

A-25

-continued

Table 7 - continued






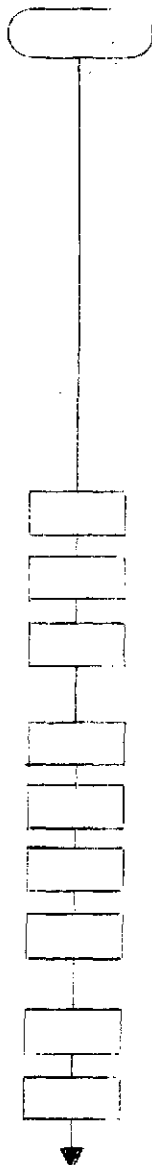



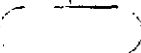


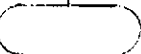
Symbol	Program Line Numbers	Description	Comments
	5680	ERT1 = -DTREQ	If it is not, then assume that the available temperature difference is zero and the error is equal to the required temperature difference.
	5690	RETURN	
① 	5700	$DTAVA = \frac{T6A - T5}{\ln \frac{T - T5}{T - T6A}}$	The available temperature drop is the log mean of the module cooling air temperature difference at the inlet and the outlet of the cooling air passages.
	5710	ERT1 = DTAVA - DTREQ	
A-26 	5720	RETURN	

TABLE 8 HEAT BALANCE FUNCTION WITH VARIABLE COOLING AIR FLOW RATE

<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
 A-27	5750	FUNCTION ERT(V)	The input parameter is the cooling air flow rate, Cfm/cell. The output parameter ERT is the difference between the available and required module-cooling air temperature differences. Inputs taken from common storage include the inlet cooling air and cathode air temperature, the cooling air heat load, the cooling air specific heat, the number of active cells, and the module temperature. Outputs through common storage include the heat transfer coefficient, the fin efficiency, the outlet cooling air temperature, the available temperature difference, and the required temperature difference.
	5760-5780		
	5790	IF $(V \leq 1) HC = 1.97V^{0.3333}$	Calculate the heat transfer coefficient.
	5800	IF $(1 < V < 2.9883) HC = 1.21 + 0.34V + 0.42V^2$	
	5810	IF $(2.9883 \leq V \leq 4) HC = 2V$	
	5820	IF $(4 < V) HC = 2.639016V^{.8}$	
	5830	ETA=1	Calculate the fin efficiency.
	5840	IF $(0.32194 < V \leq 24.72) ETA = 1.0644 - 0.1135V^{0.5}$	
	5850	IF $(24.72 \leq V) ETA = 2.486V^{-0.5}$	
	5860	$T6A = T5 + \frac{DHC}{V(CPA)N}$	

-continued-

Table 8 - continued

Symbol	Program Line Numbers	Description	Comments
	5870	$DTREQ = \frac{DHC}{N} \left(0.376 + \frac{3.876}{HC(ETA)} \right)$	Calculate the required temperature difference from the cooling air heat load, resistance in the fins, and resistance in the stagnant air film.
	5880	IF (T6A < T2) BRANCH	Branch and calculate the log mean temperature difference only if the outlet cooling air temperature is less than the module temperature
	5890	ERT = -DTREQ	There is no available temperature difference. The error ERT is minus the required temperature difference.
	5900	RETURN	
	5910	$DTAVA = \frac{T6A - T5}{\ln \frac{T2 - T5}{T2 - T6A}}$	Log mean module cooling air temperature difference.
	5920	ERT=DTAVA-DTREQ	
	5930	RETURN	

A-28

TABLE 9 RANGE TEST SUBROUTINE

Program Line
Numbers

Symbol

Description

Comments

5960

SUBROUTINE T(VARNAM,VAR,BOT,
TOP,I)

Subroutine input parameters are the variable, value, the lower and upper limits, and the out-of-range counter. The subroutine simply prints a message containing the first four parameters when the variable is out-of-range.

5970

COMMON IOU

The message is printed on output device IOU.

5980

IF (BOT \leq VAR \leq TOP) BRANCH

The subroutine ends immediately if the variable is in range.

5980

RETURN

5990

WRITE, VARNAM, VAR, BOT, TOP

6000

I=I+1

6010

RETURN

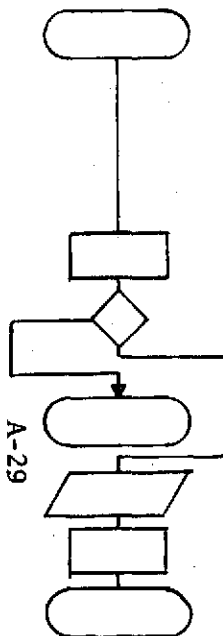


TABLE 10 BASE PROGRAM LISTING

BASE

```

100C
110C      *** CS-6 MATH MODEL BASE PROGRAM ***
120C
130$TTY,84
140$NDM
150 REALN,I
160 COMMON IOUT,CPA,CPH,DHC,DHA,DHH,HEATLD,DTREQ,DTAVA,N,I,E,
170&HC,ETA,V1,V3,V5A,T6A,T5,T3,T1,T2
180 EXTERNAL ERT,ERT1,PHTO
190 DATA CPA,CPH/1.0765,1.0666/
200&U1,U2,U3,U4/51.7007,386.7,3.419,28.32/
210&C782,C562,C561,C12132/2.25E-5,1.303E-5,.0101,8.6118E-4/
220 C5132=C562+C12132
230 C5131=C561
240 QA=C5132-C782
250 IOUT=1
260 PRINT,"FILE INPUT (T OR F)",!*
270 READ,?FIN
280 INP=50
290 IF(?FIN)INP=2
300 IF(?FIN)CALL OPENF(2,"MATHIN")
310 PRINT,"FILE OUTPUT (T OR F)",!*
320 READ,?FOUT
330 IF(.NOT.?FOUT)IOUT=66
340 GOTO6
350 1 CONTINUE
360 IF(.NOT.?FOUT)GOTO6
370 IF(.NOT.?FIN)PRINT,"FILE FOR OUTPUT",!*
380 READ(INP,48)FNAME
390 48 FORMAT(A6)
400 IF(FNAME.EQ."WAIT")GOTO6
410 END FILE 1
420 CALL CLOSEF(1,FNAME,?)
430 REWIND 1
440 6 CONTINUE
450 IF(.NOT.?FIN)PRINT,"INPUT DATA",!*
460 READ(INP,)POPSA,PCO,POOPSA,P8PSA,T7,V7,DW7,P4PSA,T9,V9SL,Dw9,
470&N,I,DELT1,V1,PWPEN,HTPEN,H2OPEN,OXPEN,NFLAG
480C
490C      INPUT DATA PLAYBACK:
500C
510 WRITE(IOUT;4)
520 WRITE(IOUT;230)
530 4 FORMAT(//////)
540 230FORMAT(" *****INPUT DATA*****")
550 WRITE(IOUT;1017)
560 1017FORMAT(" CABIN ATMOSPHERE:")
570 WRITE(IOUT;944)"POPSA",POPSA,"PCO",PCO,"POOPSA",POOPSA
580 WRITE(IOUT;1032)
590 1032FORMAT(" PROCESS AIR OUTLET/INLET:")

```

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DATA IS POOR

Table 10 - continued

```

600 WRITE(IOUT;944)"P8PSA",P8PSA,"T7 ",T7,"V7 ",V7,"DW7",DW7
610 WRITE(IOUT;1031)
620 1031FORMAT(" H2 OUTLET/INLET:")
630 WRITE(IOUT;944)"P4PSA",P4PSA,"T9 ",T9,"V9SL",V9SL,"DW9",DW9
640 WRITE(IOUT;1020)
650 1020FORMAT(" MODULES:")
660 WRITE(IOUT;944)"N ",N,"I ",I,"DELT1",DELT1,"V1 ",V1
670 WRITE(IOUT;1021)
680 1021FORMAT(" PENALTY WEIGHT FACTORS:")
690 WRITE(IOUT;944)"PWPEN",PWPEN,"HTPEN",HTPEN,"H2OPEN",H2OPEN,
700&"OXPEN",OXPEN
710 WRITE(IOUT;1022)
720 1022FORMAT(" PROGRAM CONTROL:")
730 WRITE(IOUT;944)"NFLAG",NFLAG
740 WRITE(IOUT;220)
750 220 FORMAT(" *****RESULTS*****")
760C
770C CHECK INPUTS:
780C
790 IR=0
800 CALLT("POPSA ",POPSA,13.7,15.7,IR)
810 CALLT("PCO ",PCO,.5,10.,IR)
820 CALLT("POOPSA",POOPSA,2.,4.,IR)
830 CALLT("P8PSA ",P8PSA,13.7,15.7,IR)
840 CALLT("T7 ",T7,44.,80.,IR)
850 CALLT("V7 ",V7,0.,600.,IR)
860 CALLT("DW7 ",DW7,41.,70.,IR)
870 CALLT("P4PSA ",P4PSA,14.8,21.2,IR)
880 CALLT("T9 ",T9,65.,75.,IR)
890 CALLT("V9SL ",V9SL,0.,18.,IR)
900 CALLT("DW9 ",DW9,10.,75.,IR)
910 CALLT("N ",N,90.,96.,IR)
920 CALLT("I ",I,2.44,9.76,IR)
930 CALLT("DELT1 ",DELT1,10.,25.,IR)
940 CALLT("V1 ",V1,19.2,76.8,IR)
950 CALLT("PWPEN ",PWPEN,0.,2.,IR)
960 CALLT("HTPEN ",HTPEN,0.,2.,IR)
970 CALLT("H2OPEN",H2OPEN,0.,500.,IR)
980 CALLT("OXPEN ",OXPEN,0.,3000.,IR)
990 FLAG=NFLAG
1000 CALLT("NFLAG ",FLAG,0.,1.,IR)
1010 IF(IR.GT.0)GOTO1
1020C
1030C CHECK FOR SUFFICIENT H2:
1040C
1050 V9MSL=1.3*N*I*7.508E-3
1060 IF(V9SL.GE.V9MSL)GOTO1213
1070 WRITE(IOUT;213)V9MSL
1080 213 FORMAT(" INSUFFICIENT H2.",G10.4," SLPM IS REQUIRED")
1090 GOTO1

```

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Table 10 - continued

```
1100 1213 CONTINUE
1110C
1120C CHECK CATHODE AIR CAPACITY:
1130C
1140 IF(V1.LE.70)GOTO9001
1150 V1=70.
1160 WRITE(IOUT;9000)
1170 9000FORMAT(" V1 HAS BEEN CHANGED TO 70 SCFM, BLOWER CAPACITY.")
1180 9001 CONTINUE
1190C
1200C CALC. COOLING AIR FLOW WITH COOLING BLOWERS OFF:
1210C
1220 V7M1=V7-V1
1230 QB=C5131+2.*C782*V7M1
1240 QC=C782*V7M1**2
1250 V5MIN=(-QB+SQRT(QB*QB+4.*QA*QC))/(2.*QA)
1260C
1270C CALC. COOLING AIR HEAT LOAD, ETC. FOR INPUT MODULE TEMP:
1280C
1290 DW1=DW7
1300 T2=DW1+DELT1
1310 T2INP=T2
1320 E=.729-.22*ALOG(1)+.008*I+.005*(T2-78.)
1330 HEATLD=N*I*(1.25-E)*U3
1340 T1=T7
1350 T3=T9
1360 V3=V9SL/U4
1370 T5=T1
1380 DHA=V1*CPA*(T2-T1)
1390 DHH=V3*CPH*(T2-T3)
1400 DHC=HEATLD-DHA-DHH
1410C
1420C CHECK NEED FOR COOLING:
1430C
1440 IF(DHC.GT.0)GOTO898
1450C
1460C CALC. NEW MODULE TEMP IF COOLING BLOWERS ARE OFF:
1470C
1480 888 CONTINUE
1490 V5=V5MIN
1500 V5A=N*V5MIN/96.
1510 CALL TDRIFT
1520 DROP=T2INP-T2
1530 WRITE(IOUT;944)"V5MIN",V5MIN
1540 WRITE(IOUT;469)DROP,T2INP,T2
1550 469 FORMAT(" COOLING BLOWERS ARE OFF."/ " MODULE TEMPERATURE FALLS",
1560 2F6.2,"F BELOW THE DESIRED",F6.2,"F TO",F6.2,"F.")
1570 GOTO766
1580C
1590C CHECK THAT MODULE TEMP IS HIGH ENOUGH TO TRANSFER HEAT
```

Table 10 - continued

```

1600C   AT LEAST TO COOLING FIN ROOTS:
1610C
1620 898 CONTINUE
1630 IF(T2-T5.GE..376*DHC/N)GOTO765
1640C
1650C   CALC. NEW MODULE TEMP IF COOLING BLOWERS ARE ON FULL:
1650C
1670 886 CONTINUE
1680 V5=440.
1690 V5A=V5*N/96.
1700 CALL TDRIFT
1710 RISE=T2-T2INP
1720 WRITE(IOUT;479)RISE,T2INP,T2
1730 479 FORMAT(" COOLING BLOWERS ARE ON FULL."/" MODULE TEMPERATURE RISES",
1740&F6.2,"F ABOVE THE DESIRED",F6.2,"F TO",F6.2,"F.")
1750 GOTO766
1760C
1770C   CALC. COOLING AIR FLOW FOR INPUT MODULE TEMPERATURE:
1780C
1790 765 CONTINUE
1800 VA=1.01*DHC/(CPA*N*(T2-T5))
1810 VB=2.*VA
1820 V5A=N*ROOT(VA.VB,ERT,0...005,.001,20)
1830 V5=96.*V5A/N
1840 V5INP=V5
1850C
1860C   ARE COOLING BLOWERS OUT OF RANGE:
1870C
1880 IF(V5.LT.V5MIN)GOTO888
1890 IF(V5.GT.440.)GOTO886
1900 WRITE(IOUT;3950)
1910 3950 FORMAT(" DESIRED MODULE TEMPERATURE IS MAINTAINED WITH",
1920&" COOLING BLOWERS AT PARTIAL CAPACITY.")
1930C
1940C   MODULE HEAT BALANCE IS MAINTAINED WITH COOLING BLOWERS IN RANGE:
1950C
1960 766 CONTINUE
1970 V10=V7-V1-V5
1980 WRITE(IOUT;944)"V5INP",V5INP
1990C
2000C   CHECK PLENUM BYPASS FLOW:
2010C
2020 IF(V10.GE..05*V7)GOTO244
2030 WRITE(IOUT;242)
2040 WRITE(IOUT;944)"V10",V10
2050 242FORMAT(" INSUFFICIENT INLET PROCESS AIR TO ",
2060&"PREVENT BACKMIXING THROUGH PLENUM BYPASS.")
2070 GOTO1
2080C
2090C   CALC. STREAM PARAMETERS REQUIRED FOR MOISTURE BALANCE CHECKS:

```


Table 10 - continued

```

2100C
2110 244 CONTINUE
2120 COR34=(14.1/P4PSA)**.8
2130 P4=P4PSA*U1
2140 V3SL=V9SL
2150 DP34=.3822*COR34*V3SL
2160 IF(V3SL.GT.22.)DP34=COR34*(8.3183+.4187*(V3SL-21.5801)**1.75)
2170 P3=P4+DP34
2180 P3PSA=P3/U1
2190 COR93=(14.1/P3PSA)**.8
2200 DP93=COR93*10.64*V3SL
2210 IF(V3SL.GT.6.2)DP93=COR93*(35.14*V3SL-195.25+EXP(7.75-.6537*V3SL))
2220 P9=P3+DP93
2230 P9PSA=P9/U1
2240 DP78=C782*V10*V10
2250 P8=P8PSA*U1
2260 P7=P8+DP78
2270 P7PSA=P7/U1
2280 DP12=V1*(.001903*V1+.04877)
2290 P1=P7
2300 P2=P1-DP12
2310 PC1=PC0*P7PSA/POPSA
2320 CURDEN=I/.244
2330 DELT1E=T2-DW1
2340 TI=TICOR(PC1,V1/96.,CURDEN,DELT1E)
2350 OCON=6.5803E-4*N*I
2360 CTRANS=TI*OCON
2370 HCON=OCON*2.016/16.
2380 WPROD=OCON+HCON
2390 VC4=CTrans*U2/(44.01*60.)
2400 PW9=PHTO(DW9)
2410 PW3=P3*PW9/P9
2420 VH3=V3*(1.-PW3/P3)
2430 VH4=VH3-HCON*U2/(2.016*60.)
2440C TRIAL VALUE OF H2+CO2 OUTLET WATER VAPOR PRESSURE:
2450 PW4=PHTO(T2-6.)
2460 VW4=PW4*(VC4+VH4)/(P4-PW4)
2470 DW1=DW7
2480 PW1=PHTO(DW1)
2490 VW1=V1*PW1/P1
2500 V#3=V3-VH3
2510 VWPROD=WPROD*U2/(18.01*60.)
2520 VW2=VW1+VW3-VW4+VWPROD
2530 P00=PO0PSA*U1
2540 P07=P00*P7PSA/POPSA
2550 P01=P07
2560 PN1=P1-P01-PW1-PC1
2570 VN1=V1*PN1/P1
2580 V01=V1*P01/P1
2590 VC1=V1*PC1/P1

```

Table 10 - continued

```

2600 VN2=VN1
2610 V02=V01-000N*U2/(32.*60.)
2620 VC2=VC1-VC4
2630 V2=V02+VN2+VW2+VC2
2640 PW2=VW2*P2/V2
2650 DW2=DEWT(PW2)
2660C
2670C  CHECK MODULE MOISTURE BALANCE:
2680C
2690 DDP1=T1-DW1
2700 DDP2=T2-DW2
2710 IF(ABS(DDP1-11.25).LE.1.75 .AND. ABS(DDP2-11.25).LE.1.75)GOTO30
2720 IF(DDP1.LT.4.)GOTO1210
2730 IF(DDP1.GT.14.)GOTO1210
2740 IF(DDP2.LT.7.)GOTO1211
2750 IF(DDP2.GT.19.)GOTO1211
2760 DPTDAV=.5*(DDP1+DDP2)
2770 IF(ABS(DPTDAV-11.).LE.1.5 .AND. (DDP2.GE.13. .OR. DPTDAV.GE.10.))GOTO30
2780 WRITE(IOUT;654)
2790 654FORMAT(" AVERAGE CATHODE AIR DEWPOINT DEPRESSION OUT OF RANGE.")
2800 28 WRITE(IOUT;543)
2810 WRITE(IOUT;944)"T1 ",T1,"DDP1",DDP1,"T2 ",T2,"DDP2",DDP2
2820 543FORMAT(" ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.")
2830 IF(NFLAG.EQ.1)GOTO1
2840 GOTO30
2850 1210 WRITE(IOUT;432)
2860 432FORMAT(" INLET CATHODE AIR DEWPOINT DEPRESSION OUT OF RANGE.")
2870 GOTO28
2880 1211 WRITE(IOUT;321)
2890 321FORMAT(" OUTLET CATHODE AIR DEWPOINT DEPRESSION OUT OF RANGE.")
2900 GOTO28
2910C
2920C  COMPLETE ALL STREAM DEFINITIONS:
2930C
2940 30 CONTINUE
2950 DELT1P=22.-T1+DW2
2960 T2P=DW1+DELT1P
2970 PW7=PW1
2980 PN7=PN1
2990 PC7=PC1
3000 VC7=PC7*V7/P7
3010 VW7=PW7*V7/P7
3020 PC7=PC1
3030 V07=PC7*V7/P7
3040 VN7=PN7*V7/P7
3050 RH7=100.*PW7/PHTO(T7)
3060 FC1=VC1*44.01*60./U2
3070 FW1=VW1*18.01*60./U2
3080 RH1=RH7
3090 PH3=P3-PW3

```

Table 10 - continued

3100 $FH3 = VH3 * 2.016 * 60. / U2$
3110 $EMOD = 16. * E$
3120 $POWER = N * I * E$
3130 $TE = TI / .0275$
3140 $PC2 = VC2 * P2 / V2$
3150 $FC2 = FC1 - CTRANS$
3160 $FW2 = VW2 * 18.01 * 60. / U2$
3170 $RH2 = 100. * PW2 / PHTO(T2)$
3180 $T4 = T2$
3190 $V9 = V3$
3200 $DW4 = .77 * (DW1 + DW2) / 2. + .23 * T2$
3210 $PW4 = PHTO(DW4)$
3220 $VW4 = PW4 * (VH4 + VC4) / (P4 - PW4)$
3230 $V4 = VH4 + VC4 + VW4$
3240 $V4SL = V4 * U4$
3250 $VC4SL = VC4 * U4$
3260 $VH4SL = VH4 * U4$
3270 $FC4 = CTRANS$
3280 $FH4 = VH4 * 2.016 * 60. / U2$
3290 $FW4 = VW4 * 18.01 * 60. / U2$
3300 $F4 = FC4 + FH4 + FW4$
3310 $CHWRT0 = FC4 / FH4$
3320 $HCVRT0 = VH4 / VC4$
3330 $P5 = P7$
3340 $DP56 = V5 * (V5 * C562 + C561)$
3350 $P6 = P5 - DP56$
3360 $T6 = (V5A * T6A + (V5 - V5A) * T5) / V5$
3370 $IF(V1.LE.62.)PWRCTB = 2.8 * V1 + 153.8$
3380 $IF(V1.GT.62..AND.V1.LE.65.)PWRCTB = 40. * V1 - 2150.$
3390 $IF(V1.GT.65.)PWRCTB = -34. * V1 + 2660.$
3400 $T11 = T2 + PWRCTB * U3 / (V1 * CPA)$
3410 $V11 = V2$
3420 $P11 = P8$
3430 $PWRCLB = 0.$
3440 $DP1213 = C12132 * V5 * V5$
3450 $IF(V5.LT.1.01 * V5MIN)GOTO14$
3460 $DP1213 = C12132 * V5MIN * V5MIN$
3470 $TR = (DP78 / 1.869 + .05) / 1.3$
3480 $TR = TR * (.128 + .102 * DP78 / 1.869)$
3490 $PWH = 410. - .00396 * (V5 - 368) ** 2$
3500 $PWL = 410. - .00178 * (V5 - 306.) ** 2$
3510 $PWRCLB = TR * PWH + (1. - TR) * PWL$
3520 14CONTINUE
3530 $P12 = P8 + DP1213$
3540 $T12 = T6 + PWRCLB * U3 / (V5 * CPA)$
3550 $T13 = T12$
3560 $V12 = V5$
3570 $P13 = P8$
3580 $V13 = V5$
3590 $V8 = V10 + V2 + V5$

continued-

Table 10 - continued

```

3600 VW8=VW7+VW2-VW1
3610 VC8=VC7-VC4
3620 PC8=VC8*P8/V8
3630 VN8=VN7
3640 PN8=VN8*P8/V8
3650 V08=V07-.5*(VH3-VH4)
3660 PW8=P8*VW8/V8
3670 DW8=DEWT(PW8)
3680 T8=(T11*V11+T13*V13+T7*V10+POWER*U3/CPA)/V8
3690 RH8=100.*PW8/PHTO(T8)
3700 AV7=V7*(T7+460.)*1.434/P7
3710 AV1=V1*AV7/V7
3720 AV2=V2*(T2+460.)*1.434/P2
3730 AV11=V11*(T11+460.)*1.434/P11
3740 AV9=V9*(T9+460.)*1.434/P9
3750 AV3=V3*(T3+460.)*1.434/P3
3760 AV4=V4*(T4+460.)*1.434/P4
3770 AV5=V5*AV7/V7
3780 AV6=V5*(T6+460.)*1.434/P6
3790 V6A=V5A
3800 AV6A=V6A*(T6A+460.)*1.434/P6
3810 AV12=V12*(T12+460.)*1.434/P12
3820 AV13=V13*(T13+460.)*1.434/P13
3830 AV10EX=V10*(T7+460.)*1.434/P8
3840 AV8=V8*(T8+460.)*1.434/P8
3850C
3860C EQUIVALENT WEIGHT CALCULATIONS:
3870C
3880 HRDWGT=817.9
3890 PWRPC=136.
3900 PWREC=45.
3910 PWRDAU=100.
3920 PWRTOT=PWRPC+PWREC+PWRCLB+PWRCTB+PWRDAU
3930 HTTOT=HEATLD+U3*(PWRTOT+POWER)
3940 PWRNGT=WPEN*PWRTOT
3950 HTWGT=HTPEN*HTTOT
3960 H2OWGT=H2OPEN*WPROD
3970 OXWGT=OXPEN*OCON
3980 EQWGT=PWRNGT+HTWGT+H2OWGT+OXWGT+HRDWGT
3990C
4000C MAJOR OUTPUT STATEMENTS
4010C
4020 WRITE(IOUT;456)DELT1P,T2P,DW1,DELT1P
4030 456 FORMAT(" PREFERRED VALUE OF DELT1 IS",F6.2,
4040&" UNDER THESE CONDITIONS"/" SO THAT",F6.2,
4050&" = T2 = DW1 + DELT1 =",F6.2," +",F6.2,".")
4060C
4070 944FORMAT(5X,A6,G10.4,3(" ! ",A6,G10.4))
4080C
4090 WRITE(IOUT;1020)

```

Table 10 - continued

```

4100 WRITE(IOUT;944)"TI ",T1,"TE ",TE,"E ",E,"EMOD",EMOD,
4110&"CTrans",CTrans,"OCON",OCON,"HCON",HCON,"WPROD",WPROD,
4120&"CURDEN",CURDEN,"HEATLD",HEATLD,"POWER",POWER
4130C
4140 WRITE(IOUT;1014)
4150 1014FORMAT(" CATHODE AIR INLET:")
4160 WRITE(IOUT;944)"P1 ",P1,"PC1",PC1,
4170&"PW1",PW1,"FC1",FC1,"FW1",FW1,"VC1",VC1,"VW1",VW1,
4180&"VO1",VO1,"VN1",VN1,"T1 ",T1,"DW1",DW1,"RH1",RH1
4190C
4200 WRITE(IOUT;1024)
4210 1024FORMAT(" CATHODE AIR OUTLET:")
4220 WRITE(IOUT;944)"P2 ",P2,"DP12",DP12,"PC2",PC2,
4230&"PW2",PW2,"V2 ",V2,"VC2",VC2,"VW2",VW2,
4240&"VO2",VO2,"VN2",VN2,"FC2",FC2,"FW2",FW2,"T2 ",T2,"DW2",DW2,"RH2",RH2
4250&"P11",P11,"V11",V11,"T11",T11
4260C
4270 WRITE(IOUT;1010)
4280 1010FORMAT(" PROCESS AIR INLET:")
4290 WRITE(IOUT;944)"P7 ",P7,"PW7",PW7,"PN7",PN7,"VC7",VC7,"VW7",VW7,"VO7",VO7,
4300&"VN7",VN7,"DW7",DW7,"RH7",RH7
4310C
4320 WRITE(IOUT;1015)
4330 1015FORMAT(" PROCESS AIR OUTLET:")
4340 WRITE(IOUT;944)"P8 ",P8,"PC8",PC8,"V10",V10,"DP78",DP78,
4350&"V8 ",V8,"VW8",VW8,"VC8",VC8,"VO8",VO8,"PW8",PW8,"T8 ",T8,
4360&"DW8",DW8,"RH8",RH8
4370C
4380 WRITE(IOUT;1019)
4390 1019FORMAT(" H2 INLET:")
4400 WRITE(IOUT;944)"P9 ",P9,"PW9",PW9,"DP93",DP93,"P3 ",P3
4410&"PW3",PW3,"PH3",PH3,"V3 ",V3,"VH3",VH3,"VW3",VW3,"FH3",FH3,"V9MSL",V9MSL
4420C
4430 WRITE(IOUT;1013)
4440 1013FORMAT(" H2 OUTLET:")
4450 WRITE(IOUT;944)"P4 ",P4,"DP34",DP34,"PW4",PW4,"V4 ",V4,"VC4",VC4,
4460&"VH4",VH4,"VW4",VW4,"V4SL",V4SL,"VC4SL",VC4SL,"VH4SL",VH4SL,"F4 ",F4,
4470&"FC4",FC4,"FH4",FH4,"FW4",FW4,"DW4",DW4,"CHWRT0",CHWRT0,"HCVRT0",HCVRT0
4480C
4490 WRITE(IOUT;1023)
4500 1023FORMAT(" HEAT BALANCE, MODULES:")
4510 WRITE(IOUT;944)"HEATLD",HEATLD,"DHA",DHA,"DHH",DHH,"DHC",DHC
4520C
4530 WRITE(IOUT;1012)
4540 1012FORMAT(" COOLING AIR:")
4550 WRITE(IOUT;944)"P5 ",P5,"DP56",DP56,"P6 ",P6
4560&"V5 ",V5,"T5 ",T5,"T6 ",T6,"HC ",HC,"ETA",ETA
4570&"V5A",V5A,"T6A",T6A
4580&"P12",P12,"V12",V12,"T12",T12,"DP1213",DP1213,"V5MIN",V5MIN
4590C

```

Table 10 - continued

```

4600 WRITE(IOUT;1041)
4610 1041FORMAT(" ACTUAL VOLUMETRIC FLOW RATES:")
4620 WRITE(IOUT;944)"AV1",AV1,"AV2",AV2,"AV3",AV3,"AV4",AV4,"AV5",AV5,
4630&"AV6",AV6,"AV6A",AV6A,"AV7",AV7,"AV8",AV8,"AV9",AV9,
4640&"AV10EX",AV10EX,"AV11",AV11,"AV12",AV12,"AV13",AV13
4650C
4660 WRITE(IOUT;1016)
4670 1016FORMAT(" EQUIVALENT WEIGHT:")
4680 WRITE(IOUT;944)"PWRCLB",PWRCLB,"PWRCTB",PWRCTB,"PWRPC",PWRPC,
4690&"PWREC",PWREC,"PWRDAU",PWRDAU,"PWRTOT",PWRTOT,"HTTOT",HTTOT,
4700&"PWRWGT",PWRWGT,"HTWGT",HTWGT,"H2OWGT",H2OWGT,"OXWGT",OXWGT,
4710&"HRDWGT",HRDWGT,"EQWGT",EQWGT
4720 GOTO1
4730 END
4740C
4750 FUNCTIONPHTO(TF)
4760 DATA A,B,C,D,EE,F,G/3.2437814,.00586826,1.1702379E-8,
4770&.0021878462,5.219603,273.16,2.3025851/
4780 TC=(TF-32.)/1.8
4790 X=374.11-TC
4800 PHTO=EXP(G*(EE-(X/(TC+F)))*(A+B*X+C*X**3)/(1.0+D*X)))
4810 RETURN
4820 END
4830C
4840 FUNCTION DEWT(P)
4850 EXTERNAL ROOT,PHTO
4860 XX=ALOG(P)
4870 TA=-2.4+20.25*XX+1.522*XX**2
4880 TB=TA+.1
4890 DEWT=ROOT(TA,TB,PHTO,P,.005,.005,5)
4900 RETURN
4910 END
4920C
4930 FUNCTION TICOR(P,AF,CD,DEL)
4940 REAL S(5,7)
4950 DATA S/1.75187,-.511449,.0775073,-.00592584,.000179862,
4960&1.42306,-.271935,.0210187,-.00034839,-1.8475E-5,
4970&1.08190,-.110821,-.0081408,.00196359,-8.5832E-5,
4980&.90258,-.105068,.0025161,.00028694,-1.3673E-5,
4990&.71551,-.072213,.0024297,9.08E-6,-3.48E-7,
5000&.61612,-.055237,.0003803,.00028605,-1.5623E-5,
5010&.52087,-.035109,-.0014939,.00035115,-1.4808E-5/
5020 PA=P*(AF/.44)**((.84*P+1.)*EXP(-.84*P))
5030 J=CD/5.-1.
5040 IF(J.LT.1)J=1
5050 TI1=PA*(S(1,J)+PA*(S(2,J)+PA*(S(3,J)+PA*(S(4,J)+PA*S(5,J))))
5060 IF(J.LT.7)GO TO 8
5070 TICOR=TI1
5080 GOTO9
5090 8 J=J+1

```

Table 10 - continued

```

5100 TI2=PA*(S(1,J)+PA*(S(2,J)+PA*(S(3,J)+PA*(S(4,J)+PA*S(5,J))))
5110 AII=J
5120 TERP=CD/5.-AII
5130 TICOR=TI2*TERP+TI1*(1.-TERP)
5140 9 TICOR=TICOR*(1.+0.3536*(DEL-18.33))
5150 RETURN
5160 END
5170C
5180 FUNCTION ROOT(X1,X2,YFCN,W,XTOL,YTOL,K)
5190 COMMON IOUT
5200 EXTERNAL YFCN
5210 XA=X1
5220 XB=X2
5230 FA=YFCN(XA)-W
5240 FB=YFCN(XB)-W
5250 DO 91 IROOT=1,K
5260 XN=(FA*XB-FB*XA)/(FA-FB)
5270 FN=YFCN(XN)-W
5280 IF(ABS(FN).LT.YTOL .AND.
5290& ABS(XN-XB).LT.XTOL)GO TO 99
5300 IF(IROOT.GE.K)WRITE(IOUT;200)X1,X2,W,XTOL,YTOL,IROOT,
5310& XA,XB,XN,FA,FB,FN
5320 200 FORMAT( " NONCONVERGENCE IN ROOT",5G11.4,I3/7G11.4)
5330 XA=XB
5340 XB=XN
5350 FA=FB
5360 FB=FN
5370 91 CONTINUE
5380 99 ROOT=XN
5390 RETURN
5400 END
5410C
5420 SUBROUTINE TDRIFT
5430 REAL N,I
5440 COMMON IOUT,CPA,CPH,DHC,DHA,DHH,HEATLD,DTREQ,DTAVA,N,I,E,
5450&HC,ETA,V1,V3,V5A,T6A,T5,T3,T1,T2
5460 EXTERNAL ERT,ROOT,ERT1
5470 ENTHPR=V1*CPA*T1+V3*CPH*T3
5480 T2HIGH=(ENTHPR+.99*HEATLD)/(V1*CPA+V3*CPH)
5490 T2LOW=(ENTHPR+V5A*CPA*T5+HEATLD)/(V1*CPA+V3*CPH+V5A*CPA)
5500 T2=T2HIGH
5510 DUMMY=ERT(V5A/N)
5520 T2=ROOT(T2HIGH,T2LOW,ERT1,0.,.005,.005,20)
5530 RETURN
5540 END
5550C
5560 FUNCTION ERT1(T)
5570 REAL N,I
5580 COMMON IOUT,CPA,CPH,DHC,DHA,DHH,HEATLD,DTREQ,DTAVA,N,I,E,
5590&HC,ETA,V1,V3,V5A,T6A,T5,T3,T1,T2

```

Table 10 - continued

```

5600 E=.729-.22*ALOG(I)+.008*I+.005*(T-78.)
5610 HEATLD=N*I*(1.25-E)*3.419
5620 DHA=V1*CPA*(T-T1)
5630 DHH=V3*CPH*(T-T3)
5640 DHC=HEATLD-DHA-DHH
5650 T6A=T5+DHC/(V5A*CPA)
5660 DTREQ=DHC*(.376+3.876/(HC*ETA))/N
5670 IF(T6A.LT.T)GOTO 1086
5680 ERT1=-DTREQ
5690 RETURN
5700 1086 DTAVA=(T6A-T5)/ALOG((T-T5)/(T-T6A))
5710 ERT1=DTAVA-DTREQ
5720 RETURN
5730 END
5740C
5750 FUNCTION ERT(V)
5760 REAL N,I
5770 COMMON IOUT,CPA,CPH,DHC,DHA,DHH,HEATLD,DTREQ,DTAVA,N,I,E,
5780AHC,ETA,V1,V3,V5A,T6A,T5,T3,T1,T2
5790 IF(V.LE.1.)HC=1.97*V**(.3333)
5800 IF(V.GT.1. .AND. V.LT.2.9883)HC=1.21+V*(.34+.42*V)
5810 IF(V.GE.2.9883 .AND. V.LE.4.)HC=2.*V
5820 IF(V.GT.4.)HC=2.639016*V**(.8)
5830 ETA=1.
5840 IF(V.GT..32194 .AND. V.LT.24.72)ETA=1.0644-.1135*SQR(T(V)
5850 IF(V.GE.24.72)ETA=2.486/SQR(T(V)
5860 T6A=T5+DHC/(V*CPA*N)
5870 DTREQ=DHC*(.376+3.876/(HC*ETA))/N
5880 IF(T6A.LT.T2)GO TO 86
5890 ERT=-DTREQ
5900 RETURN
5910 86 DTAVA=(T6A-T5)/ALOG((T2-T5)/(T2-T6A))
5920 ERT=DTAVA-DTREQ
5930 RETURN
5940 END
5950C
5960 SUBROUTINET(VARNAM,VAR,BOT, TOP,I)
5970 COMMON IOUT
5980 IF(VAR.GE.BOT.AND.VAR.LE.TOP)RETURN
5990 WRITE(IOUT;10)VARNAM,VAR,BOT, TOP
6000 I=I+1
6010 RETURN
6020 10FORMAT(1X,A6,"=",G10.4," RANGE: ",2G10.4)
6030 END

```

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TABLE 11 CHECKS AND MESSAGES

1. CONDITION: An input variable is out of the prediction range.
 MESSAGE: VARIABLE = XX.XX RANGE: XX.XX XX.XX
2. CONDITION: Less than 1.3 times stoichiometric amount of H₂ is supplied.
 MESSAGE: INSUFFICIENT HYDROGEN. XXX.XX SLPM IS REQUIRED.
3. CONDITION: Cathode air blowers cannot supply the requested flow rate. Program sets the flow equal to blower capacity.
 MESSAGE: V1 HAS BEEN CHANGED TO 70 SCFM, BLOWER CAPACITY.
4. CONDITION: Not enough heat is generated in the modules to attain the setpoint module temperature.
 MESSAGE: COOLING BLOWERS ARE OFF. MODULE TEMPERATURE FALLS X.XXF BELOW THE DESIRED XX.XXF TO XX.XXF.
5. CONDITION: Process streams and cooling air cannot remove enough heat to maintain the setpoint module temperature.
 MESSAGE: COOLING BLOWERS ARE ON FULL. MODULE TEMPERATURE RISES X.XXF ABOVE THE DESIRED XX.XXF TO XX.XXF.
6. CONDITION: Normal heat balance is attained.
 MESSAGE: DESIRED MODULE TEMPERATURE IS MAINTAINED WITH COOLING BLOWERS AT PARTIAL CAPACITY.
7. CONDITION: Process air flow does not exceed cathode air plus cooling air flow by at least 5%.
 MESSAGE: INSUFFICIENT PROCESS AIR TO PREVENT BACKMIXING THROUGH PLENUM BYPASS.
8. CONDITION: Inlet process air moisture conditions are out of tolerance and will not support steady state cell operation.
 MESSAGE: INLET PROCESS AIR DEW POINT DEPRESSION OUT OF RANGE. ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.
9. CONDITION: Outlet process air moisture conditions are out of tolerance and will not support steady state cell operation.
 MESSAGE: OUTLET PROCESS AIR DEW POINT DEPRESSION OUT OF RANGE. ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.

Table 11 - continued

10. CONDITION: Average of inlet and outlet process air moisture condition is out of tolerance and will not support steady state cell operation.

MESSAGE: AVERAGE PROCESS AIR DEW POINT DEPRESSION OUT OF RANGE.
 ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.

11. CONDITION: Convergence subroutine (ROOT) did not approach a solution within the specified number of iterations.

MESSAGE: NONCONVERGENCE IN ROOT (PRINT ROOT PARAMETERS)

TABLE 12 NOMENCLATURE AND UNITS

Composite Variable Names

First Prefix	<p>P - (Partial) Pressure, mm Hg</p> <p>V - Volume Flow Rate, Scfm 70F, 760 mm Hg</p> <p>AV - Volume Flow Rate, Cfm</p> <p>F - Mass Flow Rate, Lb/Hr</p> <p>DP - Pressure Drop</p> <p>DW - Dew Point, F</p> <p>T - Temperature, F</p> <p>RH - Relative Humidity, %</p>
Second Prefix	<p>C - Carbon Dioxide (CO₂)</p> <p>O - Oxygen (O₂)</p> <p>N - Nitrogen (N₂)</p> <p>H - Hydrogen (H₂)</p> <p>W - Water (H₂O)</p> <p>(None) - Total Stream</p>
Stream Number	<p>Ø - Cabin Atmosphere</p> <p>1 - Cathode Air Modules Inlet</p> <p>2 - Cathode Air Modules Outlet</p> <p>3 - H₂ Modules Inlet</p> <p>4 - H₂ Modules Outlet</p> <p>5 - Cooling Air Inlet</p> <p>5A - Cooling Air Inlet, Active Cells</p> <p>6 - Cooling Air Outlet</p> <p>6A - Cooling Air Outlet, Active Cells</p> <p>7 - Process Air Inlet</p> <p>8 - Process Air Outlet</p> <p>9 - H₂ System Inlet</p> <p>1Ø - Plenum Bypass</p> <p>11 - Cathode Blowers Outlet</p> <p>12 - Cooling Blowers Outlet</p> <p>13 - Cooling Dampers Outlet</p>
Units Suffix	<p>(None) - Units of First Prefix</p> <p>PSA - Psia</p> <p>PSG - Psig</p> <p>SL - Slpm</p>

Additional Variable Names

A,B,C,D,EE,F,G	Constants in pH ₂ O Dew Point Equation
All,J	Indices Determine S Constants
CD	Current Density
CHWRT0	CO ₂ /H ₂ Weight Ratio, Lb CO ₂ /Lb H ₂

continued-

Table 12 - continued

CJKN	Coefficient in Pressure Drop Equation
	J = Inlet Stream Subscript
	K = Outlet Stream Subscript
	N = Degree of Term
COR34,COR93	ΔP Correction Factors for Absolute Pressure
CPA	Volumetric Specific Heat, Air, Btu/Hr-Scfm-F
CPH	Volumetric Specific Heat, H_2 , Btu/Hr-Scfm-F
CTRANS	CO_2 Transferred, Lb/Hr
CURDEN	Current Density, A/Ft ²
DELT1	Input Control Variable = T2-DP1, F
DELT1P	Preferred Value Control Variable = T2-DP1, F
DELIE	Actual Control Variable = T2-DP1, F
DHA	Enthalpy Gain of Inlet Process Air, Btu/Hr
DHC	Enthalpy Gain of Cooling Air, Btu/Hr
DHH	Enthalpy Gain of Inlet H_2 , Btu/Hr
DDP1,DDP2	Dew Point Depression, Streams 1 and 2
DPTDAV	Process Air Dew Point Depression, Average, F
DROP,RISE	T2-(DWI + DELT1), Absolute Value of Module Temperature Offset
DTAVA	Log Mean Available Temperature Drop, F
DTREQ	Required Module - Cooling Air Temperature Drop, F
E	Cell Voltage, Volt
EMOD	Module (16 Cells) Voltage
EQWGT	Total System Equation Weight
ERT,ERT1	Difference Between DTREQ and DTAVA
ESTACK	Stack Voltage, Volt
ETA	Cooling Fin Efficiency, Dimensionless, 0-1
FA,FB,FN	Dependent Values Corresponding to XA,XB,XN
?FIN	File Input Indicator
FNAME	Variable Equal to Output File Name
?FOUT	File Output Indicator
HC	Cooling Fin Heat Transfer Coefficient, Btu/Hr-Ft ² -F
HCON	H_2 Consumption, Lb/Hr
HCVRT0	H_2/CO_2 Volume Ratio, Scfm H_2 /Scfm CO_2
HEATLD	Net Heat Produced, Btu/Hr
HTPEN	Heat Rejection Penalty, Lb/Btu/Hr
HTTOT	Total Heat Rejection
HTWGT	Heat Rejection Penalty Weight
H2OPEN	H_2O Vapor Rejection Penalty, Lb/Lb/Hr
H2OWGT	H_2O Rejection Penalty Weight
I	Current, A
INP	Input Device Code: 2=File, 50=Terminal
IOUT	Output Device Code: 1=File, 66=Terminal
MATHIN	Name of Input Data File
N	Number of Cells in Circuit
NERROR	Check Violation Indicator

0 - No Violation

1 - Violation

continued-

Table 12 - continued

NFLAG,FLAG	Program Option Integer = 0 or 1
OCON	O ₂ Consumption, Lb/Hr
OXPEN	O ₂ Consumption Penalty, Lb/Lb/Hr
OXWGT	O ₂ Consumption Penalty Weight
P	Inlet pCO ₂
PA	Inlet pCO ₂ Corrected for Effect of Air Flow
POWER	Electrical Power Produced, Watt
PWPEN	Power Penalty, Lb/Watt
PWRCLB	Cooling Blower Power, Watt
PWRCTB	Cathode Blower Power, Watt
PWRDAU	Data Acquisition Unit Power, Watt
PWREC	Emergency Controller Power, Watt
PWRPC	Primary Controller Power, Watt
PWRTOT	Total Power, Watt
PWRWGT	Power Penalty Weight
QA,QB,QC	Coefficients of V5 in Quadratic Formula
S	Array containing Coefficients of PA in TI Correlation
TA,TB	Trial Values of Dew Point, F
TC,TF	Dew Point, C, F, respectively
TE	Current Efficiency, %
TERP	Current Density Interpolation Variable
TI	Transfer Index, Lb CO ₂ /Lb O ₂
T2INP	Set Point Value of T2
T2P	Preferred Value of T2
T11	TI at one of the seven current densities just below the desired current density
T12	TI at one of the seven current densities just above the desired current density
U1	Conversion Factor, mm Hg/Psi
U2	Conversion Factor, Scf/Lb Mol
U3	Conversion Factor, Btu/Hr-Watt
U4	Conversion Factor, 1/Ft ³
V,TR	Dummy and Interpolation Variables
VA,VB	Trial Values for V5
V5INP	Cooling Flow for Set Point Module Temperature
V5MIN	Cooling Flow with Blowers Off
V7M1	Plenum Inlet Flow less Cathode Air Flow
V9MSL	Minimum Flow of H ₂ Required
WAIT	Dummy File Name to Prevent Closing Output File
WPROD	Water Production, Lb/Hr
X1,X2,XA,XB,XN	Trial Values of Independent Variable in Subroutine Root

APPENDIX B CS-6 BASE PROGRAM SAMPLE OUTPUTS

<u>TABLE</u>	<u>PAGE</u>
1 Output Examples	B-2

TABLE 1 OUTPUT EXAMPLES

```

*****INPUT DATA*****
CABIN ATMOSPHERE:
  POPSA      14.70 ! PCO      2.800 ! POOPSA    3.100 !
PROCESS AIR OUTLET/INLET:
  P8PSA      14.05 ! T7      55.80 ! V7      444.0 ! DW7      48.00
H2 OUTLET/INLET:
  P4PSA      14.80 ! T9      75.00 ! V9SL     9.700 ! DW9      74.00
MODULES:
  N          96.00 ! I       4.880 ! DELT1    19.00 ! V1      54.00
PENALTY WEIGHT FACTORS:
  PWPEN      0.5910 ! HTPEN   0.1280 ! H2OPEN   134.0 ! OXPEN    1636.
PROGRAM CONTROL:
  NFLAG      0.0000 !
*****RESULTS*****
DESIRED MODULE TEMPERATURE IS MAINTAINED WITH COOLING BLOWERS AT PARTIAL CAPACITY.
VSINP       261.6 !
PREFERRED VALUE OF DELT1 IS 18.81 UNDER THESE CONDITIONS
SO THAT 66.81 = T2 = DW1 + DELT1 = 48.00 + 18.81.
MODULES:
  TI         2.184 ! TE       79.41 ! E        0.3643 ! EMOD     5.829
  CTRANS     0.6732 ! OCON     0.3083 ! HCON     0.3884E-01 ! WPROD    0.3471
  CURDEN     20.00 ! HEATLD   1419. ! POWER    170.7 !
CATHODE AIR INLET:
  P1         726.8 ! PC1      2.678 ! PW1      8.549 ! FC1     1.359
  FW1        1.775 ! VC1      0.1989 ! VW1     0.6352 ! VO1     11.39
  VN1        41.78 ! T1       55.80 ! DW1     48.00 ! RH1     75.01
CATHODE AIR OUTLET:
  P2         718.6 ! DP12     8.183 ! PC2      1.336 ! PW2     10.14
  V2         53.97 ! VC2      0.1004 ! VW2     0.7619 ! VO2     11.33
  VN2        41.78 ! FC2      0.6853 ! FW2     2.129 ! T2      67.00
  DW2        52.61 ! RH2      59.89 ! P11     726.4 ! V11     53.97
  T11        84.94 !
PROCESS AIR INLET:
  P7         726.8 ! PW7      8.549 ! PN7     562.3 ! VC7     1.636
  VW7        5.223 ! VO7      93.63 ! VN7     343.5 ! DW7     48.00
  RH7        75.01 !
PROCESS AIR OUTLET:
  P8         726.4 ! PC8      2.515 ! V10     128.4 ! DP78    0.3711
  V8         444.0 ! VW8      5.350 ! VC8     1.537 ! VO8     93.57
  PW8        8.753 ! T8       64.85 ! DW8     48.63 ! RH8     55.67
H2 INLET:
  P9         912.2 ! PW9      21.49 ! DP93    143.5 ! P3      768.7
  PW3        18.11 ! PH3      750.6 ! V3      0.3425 ! VH3     0.3344
  VW3        0.8071E-02 ! FH3     0.1046 ! V9MSL   4.573 !

```

continued-

Table 1 - continued

H2 OUTLET:

P4	765.2	!	DP34	3.566	!	PW4	10.73	!	V4	0.3132
VC4	0.9859E-01	!	VH4	0.2103	!	VW4	0.4393E-02	!	V4SL	8.871
VC4SL	2.792	!	VH4SL	5.955	!	P4	0.7513	!	FC4	0.0732
PH4	0.6577E-01	!	FW4	0.1227E-01	!	DW4	54.14	!	CHWRTO	10.24
HCVRTO	2.133	!								

HEAT BALANCE, MODULES:

HEATLD	1419.	!	DHA	651.1	!	DHH	-2.923	!	DHC	770.5
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COOLING AIR:

P5	726.8	!	DP56	3.533	!	P6	723.2	!	V5	261.6
T5	55.80	!	T6	58.54	!	HC	5.255	!	ETA	0.8770
V5A	261.6	!	T6A	58.54	!	P12	728.5	!	V12	261.6
T12	63.08	!	DP1213	2.085	!	V5MIN	49.20	!		

ACTUAL VOLUMETRIC FLOW RATES:

AV1	54.96	!	AV2	56.75	!	AV3	0.3418	!	AV4	0.3094
AV5	266.2	!	AV6	268.9	!	AV6A	268.9	!	AV7	451.9
AV8	460.0	!	AV9	0.2381	!	AV10EX	130.8	!	AV11	58.06
AV12	269.3	!	AV13	270.1	!					

EQUIVALENT WEIGHT:

PWRCLB	374.1	!	PWRCTB	305.0	!	PWRPC	136.0	!	PWREC	45.00
PWRDAU	100.0	!	PWRTOT	960.1	!	HTTOT	5285.	!	PWRWGT	567.4
HWGT	676.5	!	H2OWGT	46.51	!	OXWGT	473.5	!	HRDWGT	817.9
EQWGT	2582.	!								

*****INPUT DATA*****

CABIN ATMOSPHERE:

POPSA	14.70	!	PCO	0.6830	!	POOPSA	3.100	!
-------	-------	---	-----	--------	---	--------	-------	---

PROCESS AIR OUTLET/INLET:

P8PSA	14.05	!	T7	55.80	!	V7	444.0	!	DW7	48.00
-------	-------	---	----	-------	---	----	-------	---	-----	-------

H2 OUTLET/INLET:

P4PSA	14.80	!	T9	75.00	!	V9SL	9.700	!	DW9	74.00
-------	-------	---	----	-------	---	------	-------	---	-----	-------

MODULES:

N	96.00	!	I	4.880	!	DELT1	19.00	!	V1	54.00
---	-------	---	---	-------	---	-------	-------	---	----	-------

PENALTY WEIGHT FACTORS:

PWPEN	0.5910	!	HTPEN	0.1280	!	H2OPEN	134.0	!	OXPEN	1536.
-------	--------	---	-------	--------	---	--------	-------	---	-------	-------

PROGRAM CONTROL:

NELAC	0.0000	!
-------	--------	---

*****RESULTS*****

DESIRED MODULE TEMPERATURE IS MAINTAINED WITH COOLING BLOWERS AT PARTIAL CAPACITY.

VSINF	261.6	!
-------	-------	---

PREFERRED VALUE OF DELT1 IS 18.82 UNDER THESE CONDITIONS

SO THAT $66.82 = T2 = DW1 + DELT1 = 48.00 + 18.82$.

MODULES:

TI	0.8224	!	TE	29.91	!	E	0.3643	!	EMOD	5.829
CTRANS	0.2535	!	OCON	0.3083	!	HCON	0.3884E-01	!	WPROD	0.3471
CURDEN	20.00	!	HEATLD	1419.	!	POWER	170.7	!		

CATHODE AIR INLET:

P1	726.8	!	PC1	0.6531	!	PW1	8.549	!	FC1	0.3314
FW1	1.775	!	VC1	0.4853E-01	!	VW1	0.6352	!	V01	11.39
VN1	41.93	!	T1	55.80	!	DW1	48.00	!	RH1	75.01

Table 1 - continued

CATHODE AIR OUTLET:

P2	718.6	!	DP12	8.183	!	PC2	0.1516	!	PW2	10.15
V2	54.03	!	VC2	0.1140E-01	!	VW2	0.7630	!	V02	11.33
VN2	41.93	!	FC2	0.7796E-01	!	FW2	2.132	!	T2	67.00
DW2	52.62	!	RH2	59.91	!	P11	726.4	!	V11	54.03
T11	84.94	!								

PROCESS AIR INLET:

P7	726.8	!	PW7	8.549	!	PN7	564.3	!	VC7	0.3990
VW7	5.223	!	V07	93.63	!	VN7	344.7	!	DW7	48.00
RH7	75.01	!								

PROCESS AIR OUTLET:

P8	726.4	!	PC8	0.5920	!	V10	128.4	!	DP78	0.3711
V8	444.0	!	VW8	5.351	!	VC8	0.3619	!	V08	93.57
PW8	8.753	!	T8	64.85	!	DW8	48.63	!	RH8	55.67

H2 INLET:

P9	912.2	!	PW9	21.49	!	DP93	143.5	!	P3	768.7
PW3	18.11	!	PH3	750.6	!	V3	0.3425	!	VH3	0.3344
VW3	0.8071E-02	!	PH3	0.1046	!	V9MSL	4.573	!		

H2 OUTLET:

P4	765.2	!	DP34	3.566	!	PW4	10.73	!	V4	0.2509
VC4	0.3713E-01	!	VH4	0.2103	!	VW4	0.3520E-02	!	V4SL	7.106
VC4SL	1.051	!	VH4SL	5.955	!	F4	0.3291	!	FC4	0.2535
PH4	0.6577E-01	!	FW4	0.9835E-02	!	DW4	54.15	!	CHWRT0	3.855
HCVRT0	5.663	!								

HEAT BALANCE, MODULES:

HEATLD	1419.	!	DHA	651.1	!	DHH	-2.923	!	DHC	770.5
--------	-------	---	-----	-------	---	-----	--------	---	-----	-------

COOLING AIR:

P5	726.8	!	DP56	3.533	!	P6	723.2	!	V5	261.6
T5	55.80	!	T6	58.54	!	HC	5.255	!	ETA	0.8770
V5A	261.6	!	T6A	58.54	!	P12	728.5	!	V12	261.6
T12	63.08	!	DP1213	2.085	!	V5MIN	49.20	!		

ACTUAL VOLUMETRIC FLOW RATES:

AV1	54.96	!	AV2	56.82	!	AV3	0.3418	!	AV4	0.2478
AV5	266.2	!	AV6	268.9	!	AV6A	268.9	!	AV7	451.9
AV8	460.1	!	AV9	0.2881	!	AV10EX	130.8	!	AV11	58.12
AV12	269.3	!	AV13	270.1	!					

EQUIVALENT WEIGHT:

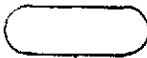



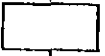




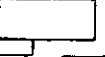
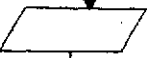
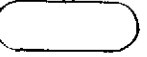

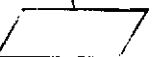
PWRCLB	374.1	!	PWRCTB	305.0	!	PWRPC	136.0	!	PWREC	45.00
PWRDAU	100.0	!	PWRTOT	960.1	!	HTTOT	5285.	!	PWRWGT	567.4
HTWGT	676.5	!	H2OWGT	46.51	!	OXWGT	473.5	!	HRDWGT	817.9
EQWGT	2582.	!								

OK

APPENDIX C CS-6 CABIN $p\text{CO}_2$ SIMULATION PROGRAM DOCUMENTATION

<u>TABLE</u>		<u>PAGE</u>
1	Main Program Flow Chart	C-2
2	Base Subroutine Flow Chart	C-11
3	Water Vapor Pressure Function	C-27
4	Dew Point Temperature Function	C-28
5	Transfer Index Function	C-29
6	Root Function	C-31
7	Module Temperature Subroutine	C-33
8	Heat Balance Function With Variable Module Temperature. .	C-34
9	Heat Balance Function With Variable Cooling Air Flow Rate	C-36
10	Range Test Subroutine	C-38
11	Mode B Current and Cathode Air Flow Subroutine	C-39
12	Cyclic Program Listing	C-40
13	Checks and Messages	C-58
14	Nomenclature and Units	C-60
15	Key to Selective Output Variables	C-64

TABLE 1 MAIN PROGRAM FLOW CHART

Symbol	Program Line Numbers	Description	Comments
		START	
	150-720		Initialize type, common, equivalence, external and data statements
	760	PRINT, "FILE INPUT (T OR F)"	Indicate from terminal whether input will be from data file MATHIN (T), or from the terminal (F).
	770	READ, QFIN	
	780	INP = 50	
	790	IF (QFIN) INP=2	
	800	IF (QFIN) CALL OPEN F(2, "MATHIN")	
	810	PRINT, "FILE OUTPUT (T OR F)"	Indicate from terminal whether output will be on a file (T) or on the terminal (F).
	820	READ, QFOUT	
	830	IF (NOT, QFOUT) IOUT=66	
	850	PRINT, "END OF INPUT DATA FILE"	Program branches to this point and terminates when a file input statement is attempted (usually line 1050) but the input file has been exhausted.
	860	CALL EXIT	
	900	IF (NOT QFOUT) BRANCH	Obtain output file name if file output is in use.
	910	IF (NOT QFIN) PRINT, "FILE FOR INPUT"	

-continued-

C-2

Table 1 - continued

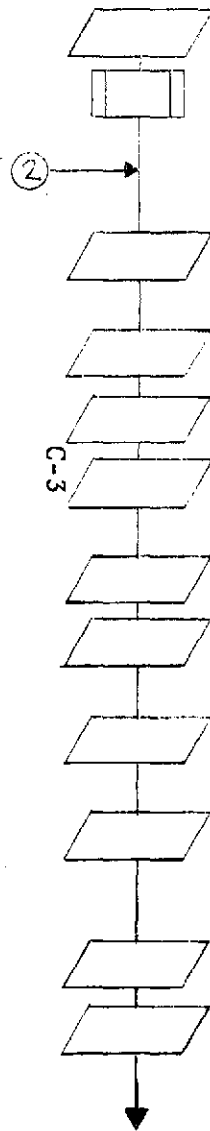
<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
	920-930	READ, FNAME	
	980	IF (FNAME ≠ "SAME") CALL CLOSEF(1, FNAME, 7)	Assign the name to the file and close it unless the name is SAME, indicating that more output will be written into the same file.
	1020-1040	IF (NOT QFIN) PRINT, "PROBLEM IDENTIFIER"	Read and write the problem identifier which may be any comments up to 84 characters long.
	1050	READ, IDENTIFIER	
	1060	IF (QFIN) PRINT, IDENTIFIER	
	1100	PRINT, "NEW CO2 GENERATION TABLE?"	Input and output new CO2 generation table if desired, or use the table stored in the program.
	1110	READ, QCO2GT	
	1120	IF(QCO2GT) READ, CO2 GENERATION TABLE	
	1130-1160	IF (QCO2GT) PRINT, CO2 GENERATION TABLE	
	1210	IF (NOT QFIN) PRINT, "INPUT DATA"	Read inputs for base, Mode B, and time intervals in the order and ranges specified in Table 1.
	1220	READ, POPSA, PCO,...,DT,DPRINT	
	1280	IF (NOT QFIN) PRINT, "PRINT BASE OUTPUT (T OR F)"	Indicate whether the base program output table should be printed (T) or omitted (F).

Table 1 - continued

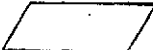




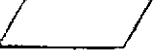
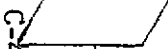







Symbol	Program Line Numbers	Description	Comments
	1290	READ, QPRINT	
	1300	KBASE = 4	
	1310	IF (QPRINT) KBASE = 5	
	1320	IF (NOT QFIN) PRINT, "NEW CYCLIC OUTPUT SUBSCRIPTS?"	Read new cyclic table output item subscripts if they are to be changed.
	1330	READ, QSUBS	
	1340	IF (QSUBS) READ, NDEX, INDEX ₁ , ..., INDEX _{NDEX}	
	1350	IF (QFOUT) PRINT, "START PROBLEM"	Print message at terminal indicating that a set of inputs is complete and calculation is beginning.
	1390	$BK_9 = \frac{BK_1 - BK_4}{BK_2 - BK_3}$	
	1400	$BK_{10} = BK_1 - BK_9(BK_2)$	Calculate slopes and intercepts for Mode B current and cathode air flow curves.
	1410	$BK_{11} = \frac{BK_5 - BK_8}{BK_6 - BK_7}$	
	1420	$BK_{12} = BK_5 - BK_{11}(BK_6)$	
	1470	IF (KMODE=1) CALL BMODE	If Mode B is in effect, determine current and cathode air flow for the initial pCO ₂ .
	1480-1780	WRITE, POPSA, PCO, ..., DT, DPRINT	Playback base, Mode B and time interval inputs with current and cathode air flow determined by Mode B if it is in effect.
	1820	IR=0	

Table 1 - continued


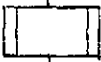


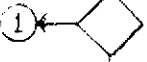
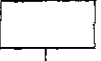
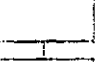
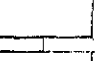
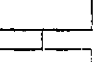
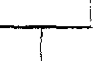
Symbol	Program Line Numbers	Description	Comments
	1830	CALL T("POPSA","POPSA,13.7,15.7,IR)	Initialize out-of-range input variable counter.
	1840-2170		
	2180	CALL T("DPRINT","",DPRINT,1,100,IR)	Subroutine T checks each input variable against its allowable range. Out-of-range variables are printed and cause IR to be incremented.
	2190	IF(IR > 0) BRANCH	
	2230	CALL BASE(KMODE,KBASE,1,KERROR)	Call BASE to determine all system parameters at time zero, to print a base output table if indicated by KBASE=5, and to abort simulation if KERROR value returned by BASE indicates that certain inputs do not support steady-state. Also abort if no. of days to be simulated = 0.
	2240	IF(KERROR #0 OR DAYS =0) BRANCH	
	2280	NDT=DT	Initialize integer variables: integration time interval, day counter, minutes per cycle (day), limit on number of days, and printing time increment.
	2290	NDAY=0	
	2300	MINCYC=TMAX(NSTEPS)	
	2310	NDAYS=DAYS	
	2320	NPRINT=DPRINT	

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	2330	$U5 = \frac{(T\emptyset + 460)(386.7)(760)}{(530)(VOLUME)(60)(44.01)}$	Calculate proportionality constant between net CO ₂ removal (Lb/Hr) and cabin pCO ₂ change rate (mm Hg/Min).
	2340	MAXDEX=0	Determine the names (HDG) of the variables to be printed out in the table versus time, and find largest subscript (MAXDEX).
	2350	DO 110 MN=1,NDEX	
	2360	IN=INDEX(MN)	
	2370	HDG(MN)=HEAD(IN)	
	2380	110 IF (IN > MAXDEX)MAXDEX=IN	
	2390	IF (1 ≤ MAXDEX ≤ 52)KBASE=1	Calculate the parameter KBASE which indicates to the BASE subroutine which of its output variables must be calculated and which sections may be omitted for faster execution.
	2400	IF (53 ≤ MAXDEX ≤ 78)KBASE=2	
	2410	IF (79 ≤ MAXDEX ≤ 129)KBASE=3	
	2420	IF (130 ≤ MAXDEX ≤ 150)KBASE=4	
	2470	QPRINT= .TRUE.	A line will be printed at time zero.
	2480	NT=0	
	2490	D0725 MN=1,NDEX	Clear the variable containing the average of the parameters, AVG.
	2500	725 AVG(MN)=0	
	2510	NDAY=NDAY + 1	Increment the day counter.
	2520	PCOI=PCO	Store the cabin pCO ₂ for the beginning of the cycle.

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	2530	IGEN=1	Initialize the CO ₂ generation rate step counter and the CO ₂ generation rate.
	2540	CO2GEN=CGEN(1)	
	2580	IF(QFOUT)PRINT, NDAY	If file output is being used, print the day counter on the terminal to indicate progress of the program to the operator.
	2590-2620	PRINT CYCLIC TABLE HEADINGS	
	2630	WRITE, 0,0	Print time at time zero.
	2640	CALL BASE(KMODE,KBASE,1,KERROR)	Call BASE to determine system parameters at time zero and to print any error messages.
	2650	IF(KERROR ≠ 0)BRANCH	If the variable KERROR indicates that conditions will not support the steady-state, then BRANCH to get the next set of input data.
	2700	IF (NOT QPRINT) BRANCH	Print a line in the cyclic table at the proper time.
	2710-2750	PRINT A LINE IN THE CYCLIC TABLE	
	2820	IF (NT < MINCYC) BRANCH	BRANCH if it is not the end of the day.
	2830	DO 726 MN=1,NDEX	Complete calculation of average system parameters.
	2840	726 AVG(MN)=AVG(MN) · $\frac{DT}{MINCYC}$	
	2850-2870	PRINT AVERAGES	

Table 1 - continued

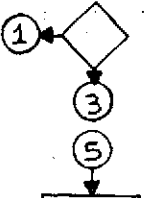

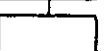
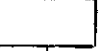
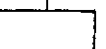
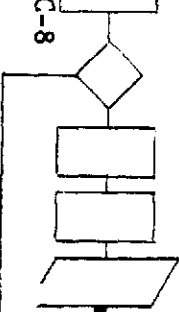

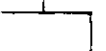
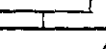
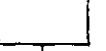
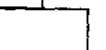
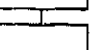
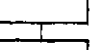

Symbol	Program Line Numbers	Description	Comments
	2880	IF (NDAY=NDAYS OR $\left \frac{PCO-PCOI}{PCO} \right < 0.0005$) BRANCH	Start a new cycle unless either steady-state has been reached or maximum number of cycles has been reached.
	2940	NT=NT + NDT	Increment time.
	2950	QPRINT=MOD(NT,NPRINT).EQ.0	Determine whether a table line will be printed at this time.
	2960	IF(NT > TMAX(IGEN)) IGEN=IGEN+1	Update CO ₂ generation rate.
	2970	CO2GEN = CGEN(IGEN)	
	3010	IF(NOT QPRINT) BRANCH	Print the time if a line of table will be printed at this time.
	3020	NHRS = NT/60	Calculate pCO ₂ at the new time. First assume that pCO ₂ has not changed during the latest time increment. Calculate the rate of pCO ₂ change at the beginning of the time increment (SLOPEA). Calculate average rate of pCO ₂ change during the time interval (SLOPE). Using the old pCO ₂ and the average slope, recalculate the new pCO ₂ . The error associated with the first trial is YA.
	3030	NMIN=NT - NHRS(60)	
	3040-3050	WRITE TIME	
	3100	XA=PCO	
	3110	SLOPEA=U5(CO2GEN-CTTRANS)	
	3120	SLOPE=SLOPEA	
	3130	PCN=PCO + SLOPE x DT	
	3140	YA=XA - PCN	

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	3150	$XB = PCN$	<p>Use the improved pCO_2 value for the second guess (XB). Call BASE to find the CO_2 removal rate based on the latest value of pCO_2. Calculate the rate of pCO_2 change at the end of the time increment and the average rate of pCO_2 change during the time increment. Recalculate pCO_2 at the end of the time interval from the pCO_2 at the beginning of the interval and the rate of pCO_2 change. YB is the error associated with the second guess at cabin pCO_2.</p>
	3160	$PCO = PCN$	
	3170	CALL BASE(KMODE,0,0,KERROR)	
	3180	IF(KERROR \neq 0) BRANCH	
	3190	$SLOPEB = U5 \times (CO2GEN - CTRANS)$	
	3200	$SLOPE = 0.5 \times (SLOPEA + SLOPEB)$	
	3210	$PCN = XA + SLOPE \times DT$	
	3220	$YB = XB - PCN$	
	3230	$PCO = \frac{YA \times XB - YB \times XA}{YA - YB}$	
6-3	3240	KPRINT=0	<p>The cabin pCO_2 at the end of the time increment is found with precision by finding the zero of the function defined by two points with coordinates (XA,YA), and (XB,YB). Linear interpolation is used because both points are already close to the root.</p>
	3250	IF(QPRINT) KPRINT=1	
	3290	CALL BASE(KMODE,KBASE,KPRINT,KERROR)	

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
①	3300	IF (KERROR \neq 0) BRANCH	
	3310-3330		Update the average system parameters.
	3360	SLOPEC=U5 x (CO2GEN-CTrans)	Check for error in cabin pCO ₂ and BRANCH to print a line of data in the cyclic table.
	3370	SLOPE = 0.5 x (SLOPEA+SLOPEC)	
	3380	PCN=XA - SLOPE x DT	
	3390	YC= PCO - PCN	
④			


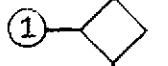
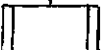
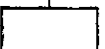







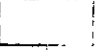
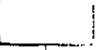
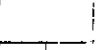
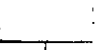
C-10

TABLE 2 BASE SUBROUTINE FLOW CHART

<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
		START	
C-11	3680	CPA = 1.0765	Initialize Constant Btu/Hr/Scfm-F
	3680	CPH = 1.0666	Initialize Constant Btu/Hr/Scfm-F
	3690	U1 = 51.7	Initialize Constant mm Hg/Psi
	3690	U2 = 386.7	Initialize Constant Scfm/Lb-Mol/Hr
	3690	U3 = 3.419	Initialize Constant Btu/Hr/Watt
	3690	U4 = 28.32	Initialize Constant 1/Ft ³
	3700	C782 = 2.25×10^{-5}	Initialize constants for pressure drop equations
	3700	C562 = 1.303×10^{-5}	
	3700	C561 = 1.01×10^{-2}	
	3700	C6132 = 8.611×10^{-4}	
	3710	C5132 = C562 + C6132	
	3710	C5131 = C561	
	3710	QA = C5132 - C782	
	3720	HRDWGT = 817.9 Lb	Initialize weight and power constants
	3720	PWRPC = 136 WATTS	
	3720	PWREC = 45 WATTS	
	3720	PWRDAU = 100 WATTS	

-continued-

Table 2 - continued

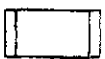

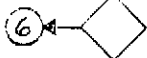

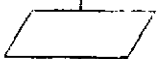




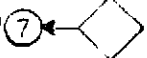

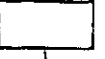

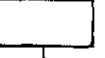





Symbol	Program Line Numbers	Description	Comments
	3730	KERROR = 0	Initialize error indicator
	3740	IF (KMODE + KBASE=0) BRANCH	
	3750	IF (KMODE=1) CALL BMODE	
	3790	$V9MSL = (1.3)(N)(I)(7.058 \times 10^{-3})$	Calc. required H ₂ flow
	3800	IF V9MSL ≤ V9SL THEN BRANCH	Check for sufficient H ₂ Flow
	3810-3820	WRITE "INSUFFICIENT H ₂ ," V9MSL, "IS REQUIRED"	Write error message and required H ₂ flow
	3830	KERROR = 1	Return in error condition
	3840	RETURN	
	3890	IF V1 ≤ 70 THEN BRANCH	Check that V1 is less than the process air blower capacity
	3900	V1 = 70	Set V1 to maximum blower capacity
	3910-3920	WRITE "AIRFLOW CHANGE TO 70 SCFM"	Print error message
	3970	V7M1 = V7 - V1	Calculate bypass cooling air flow with cooling blowers off; i.e., calculate minimum cooling air flow rate
	3980	$QB = C5131 + 2(V7M1)^2$	
	3990	$QC = C782 (V7M1)^2$	
	4000	$V5MIN = \frac{-QB + \sqrt{QB^2 + 4(QA)(QC)}}{2(QA)}$	

C-12

Table 2 - continued

Symbol	Program Line Numbers	Description	Comments
C-13	4040	DW1 = DW7	
	4050	T2 = DW1 + DELT1	Calculate cell temperature
	4060	T2INP = T2	Store input T2
	4070	$E = 0.729 - 0.22 \ln I + 0.008I + 0.005 (T2-78)$	Calculate cell voltage
	4080	HEATLD = (1.25-E) (N) (I) (U3)	Calculate modules' heatload
	4090	T1 = T7	
	4100	T3 = T9	
	4110	V3 = V9SL/U4	
	4120	T5 = T1	
	4130	DHA = V1 (CPA) (T2 - T1)	Calculate heat removed by cathode air flow
	4140	DHH = V3 (CPH) (T2-T3)	Calculate heat removed by H ₂
	4150	DHC = HEATLD-DHA-DHC	Calculate heat removed by cooling air
	4190	If DHC > 0 THEN BRANCH	Check to see if cooling air is required
④	4240	V5 = V5MIN	Set cooling air flow to minimum
⑤	4250	V5A = (N) (V5MIN)/96	Calculate flow thru active cells

Table 2 - continued

Symbol	Program Line Numbers	Description	Comments
	4260	CALL TDRIFT	Calculate T2 for subcooled condition
	4270	DROP = T2INP-T2	Calculate temperature, T2, drop
	4280	IF (DROP ≤ 3) BRANCH	
	4290	IF (KPRINT = 0) BRANCH	
	4300-4320	WRITE "V5MIN," V5MIN "COOLING BLOWERS OFF," "MODULE TEMPERATURE FALLS," DROP, "NEW T2," T2	Print out new conditions
			
			
			
			
	4390	IF $T2-T5 \geq \frac{(0.376)DHC}{N}$ THEN BRANCH	Check if there is sufficient ΔT to conduct heat up fins
	4440	V5 = 440	Set V5 to maximum blower capacity
	4450	V5A = V5(N)/96	Calculate flow thru active cells
	4460	Call TDRIFT	Calculate T2
	4470	RISE = T2-T2INP	Call rise in module temperature
	4480	IF (RISE ≤ 3) BRANCH	
	4490	IF (KPRINT = 0) BRANCH	
	4500-4520	WRITE "COOLING BLOWERS ON FULL," "MODULE TEMPERATURE RISES," RISE, "NEW T2," T2	Print out new conditions
			
			

C-14

Table 2 - continued

Symbol	Program Line Numbers	Description	Comments
	4580	$VA = 1.01 \times DHC/CPA (N) (T2-T5)$	Calculate minimum and maximum cooling air flow to set range for iterative subroutine "ROOT"
	4590	$VB = 2(VA)$	
	4600	$V5A = (N) \cdot \text{ROOT} (VA, VB, ERT, 0, 0.005, 0.001, 20)$	Calculate cooling air flow past active cells
	4610	$V5 = 96(V5A)/N$	Calculate total cooling air flow
	4620	$V5INP = V5$	
	4660	IF $V5 < V5MIN$ THEN BRANCH	Check for subcooling
	4670	IF $V5 > 440$ THEN BRANCH	Check for heatup
	4720	$V10 = V7 - V1 - V5$	Calculate plenum bypass flow
	4760	IF $V10 \geq 0.05 (V8)$ THEN BRANCH	Check for sufficient plenum bypass
	4770	IF $(KPRINT = 0)$ BRANCH	
	4780-4810	WRITE "INSUFFICIENT AIR FLOW, RECIRCULATION OF AIR FROM OUTLET TO INLET"	Print error message
	4880	IF $(KBASE = 0)$ BRANCH	
	4890	$COR34 = \frac{(14.1)}{P4PSA}^{0.8}$	Calculate module H_2 cavity pressure drop
	4900	$P4 = P4PSA (V1)$	
	4910	$V3SL = V9SL$	
	4920	$DP34 = (0.3822) (COR34) (V3SL)$	

Table 2 - continued

Symbol	Program Line Numbers	Description	Comments
	4930	IF V3SL ≤ 22 THEN BRANCH	
	4930	$DP34 = COR34 (8.3183 - 0.4187 (V3SL - 21.5801)^{1.75})$	
	4940	$P3 = P4 + DP34$	Calculate module H ₂ inlet pressure
	4950	$P3PSA = P3/U1$	
	4960	$COR93 = \frac{(14.1)^{0.8}}{P3PSA}$	
	4970	$DP93 = (COR93) (10.64) (V3SL)$	Calculate H ₂ distribution block pressure drop
	4980	IF V3SL ≤ 6.2 THEN BRANCH	
	4980	$DP93 = COR93 [35.64 V3SL - 195.25 + e^{0.75 - 0.6537 V3SL}]$	
	4990	$P9 = P3 + DP93$	Calculate H ₂ inlet pressure
	5000	$P9PSA = P9/U1$	
	5010	$DP78 = 2.25 \times 10^{-5} (V10)^2$	Calculate process air inlet pressure using plenum pressure drop correlation
	5020	$P8 = P8PSA (U1)$	
	5030	$P7 = P8 + DP78$	
	5040	$P7PSA = P7/U1$	
	5050	$DP12 = 0.001903 (V1)^2 + 0.04877 (V1)$	Calculate cathode air pressure drop
	5060	$P1 = P7$	

C-16

Table 2 - continued

Symbol	Program Line Numbers	Description	Comments
⑭	5070	$P2 = P1 - DP12$	Calculate cathode air out pressure
	5080	$CURDEN = I / 0.244$	Calculate current density
⑬	5090	$DELT1E = T2 - DW1$	Calculate actual humidity ΔT
	5110	$PC1 = PCO \frac{P7PSA}{POP SA}$	Calculate cathode inlet pCO_2
	5120	$TI = TICOR (PC1, V1/96, CURDEN, DELT1E)$	Calculate TI
	5130	$OCON = 6.5803 \times 10^{-4} (N) (I)$	Calculate O_2 consumed
	5140	$CTrans = TI (OCON)$	Calculate CO_2 transferred
C-17	5150	IF (KBASE \leq 1) RETURN	
	5160	$HCON = OCON \frac{2.016}{16}$	Calculate H_2 consumed
	5170	$WPROD = HCON + OCON$	Calculate water produced
	5180	$VC4 = CTRANS \frac{V2}{44.01 \times 60}$	
	5190	$PW9 = PHTO (DW9)$	
	5200	$PW3 = P3 \frac{PW9}{P9}$	Calculate anode gas stream parameters
	5210	$VH3 = V3 (1 - \frac{PW3}{P3})$	
	5220	$VH4 = VH3 - HCON \frac{U2}{2.016 \times 60}$	
	5240	$PW4 = PHTO (T2-6)$	
	5250	$VW4 = \frac{PW4}{P4 - PW4} (VC4 + VH4)$	

Table 2 - continued

Symbol	Program Line Numbers	Description	Comments
C-18	5260	DW1 = DW7	Calculate cathode air water balance parameters
	5270	PW1 = PHTO (DW1)	
	5280	$VW1 = V1 \frac{PW1}{P1}$	
	5290	VW3 = V3-VH3	
	5300	$VWPROD = WPROD \frac{V2}{18.01 \times 60}$	
	5310	$VW2 = VW1 + VW3 - VW4$	Calculate cathode air inlet stream parameters
	5320	POO = POOPSA/U1	
	5330	PO7 = POO (P7/PO)	
	5340	PO1 = PO7	
	5350	$PN1 = P1 - PO1 - PW1 - PC1$	
	5360	$VN1 = V1 (PN1/P1)$	Calculate cathode air outlet stream parameters
	5370	$VO1 = V1 (PO1/P1)$	
	5380	$VC1 = V1 (PC1/P1)$	
	5390	VN2 = VN1	
	5400	$VO2 = VO1 - OCON (U2/32 \times 60)$	
	5410	$VC2 = VC1 - VC4$	

Table 2 - continued






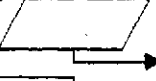


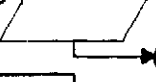

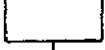

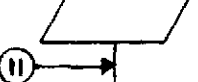
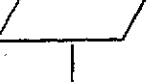
Symbol	Program Line Numbers	Description	Comments
	5420	$V2 = VO2 + VN2 + VW2 + VC2$	
	5430	$PW2 = \frac{VW2}{V2} P2$	
	5440	$DW2 = DEWT (PW2)$	
	5500	IF $T1-DW1 = 11.25 \pm 1.75$ AND $T2-DW2 = 11.25 \pm 1.75$ THEN BRANCH	
	5510	IF $T1-DW1 \geq 4$ THEN BRANCH	
	5640-5650	WRITE "INLET AIR HUMIDITY OUT-OF-RANGE"	
	5520	IF $T1-DW1 \leq 14$ THEN BRANCH	
	5530	IF $T2-DW2 \geq 7$ THEN BRANCH	Perform moisture balance checks
	5670-5680	WRITE "OUTLET AIR HUMIDITY OUT-OF-RANGE"	
	5540	IF $T2-DW2 \leq 19$ THEN BRANCH	
	5550	$DPTDAV = \frac{1}{2} (T1-DW1 + T2-DW2)$	
	5560	IF $DPTDAV = 11 \pm 1.5$ AND EITHER $T2-DW2 \geq 13$ OR $DPTDAV \geq 0$ THEN BRANCH	
	5570-5580	WRITE "AVE DEW PT DEPRESSION OUT-OF-RANGE"	
	5590-5610	WRITE "ELECTROLYTE MOISTURE BALANCE NOT MAINTAINED"	

Table 2 - continued

Symbol	Program Line Numbers	Description	Comments
	5620	KERROR = 3	
	5630	IF NFLAG = 1 THEN RETURN	Check NFLAG for program abort
	5740	IF (KBASE = 2) RETURN	
	5750	DELT1P = 22-T1 + DW2	Calculate preferred ΔT
	5760	T2P = DP1 + DELT1P	
	5770	PW7 = PW1	
	5780	PN7 = PN1	
	5790	PC7 = PC1	Complete definition of process air inlet stream
	5800	$VC7 = \frac{PC7}{P7} (V7)$	
	5810	$VW7 = \frac{PW7}{P7} (V7)$	
	5820	PO7 = PO1	
	5830	$VO7 = \frac{PO7}{P7} (V7)$	
	5840	$VN7 = \frac{PN7}{P7} (V7)$	
	5850	$RH7 = 100 \frac{PW7}{PHTO(T7)}$	
	5860	$FC1 = VC1 \frac{44.01 \times 60}{U2}$	Complete cathode air inlet stream definition

Table 2 - continued

Symbol	Program Line Numbers	Description	Comments
	5870	$FW1 = VW1 \frac{18.01 \times 60}{U2}$	
	5880	$RH1 = RH7$	Complete cathode air inlet def.
	5890	$PH3 = P3 - PW3$	Complete definition of H_2 inlet
	5900	$FH3 = VH3 \frac{2.016 \times 60}{U2}$	
	5910	$EMOD = 16(E)$	
	5920	$POWER = (N)(I)(E)$	Calculate remaining module parameters
	5930	$TE = TI/0.0275$	
	5940	$PC2 = VC2 \frac{P2}{V2}$	
	5950	$FC2 = FC1 - CTRANS$	
	5960	$FW2 = VW2 \frac{18.01 \times 60}{U2}$	Complete definition of cathode air outlet
	5970	$RH2 = 100 \frac{PW2}{PHTO(T2)}$	
	5980	$T4 = T2$	
	5990	$V9 = V3$	
	6000	$DW4 = 0.77 \frac{DW1 + DW2}{2} + 0.23T2$	Refined H_2 dew point correlation
	6010	$PW4 = PHTO(DW4)$	
	6020	$VW4 = \frac{PW4}{P4 - PW4} (VH4 + VC4)$	Complete definition of anode gas outlet
	6030	$V4 = VH4 + VC4 + VW4$	

Table 2 - continued

















Symbol	Program Line Numbers	Description	Comments
	6040	$V4SL = V4(U4)$	
	6050	$VC4SL = VC4(U4)$	
	6060	$VH4SL = VH4(U4)$	
	6070	$FC4 = CTRANS$	
	6080	$FH4 = VH4 \frac{2.016 \times 60}{U2}$	
	6090	$FW4 = VW4 \frac{18.01 \times 60}{U2}$	
	6100	$F4 = FC4 + FH4 + FW4$	
	6110	$CHWRTO = FC4/FH4$	
	6120	$HCVRTO = VHR/VC4$	
	6130	$P5 = P7$	
	6140	$DP56 = (V5)^2 C562 + V5(C561)$	Calculate cooling air pressure drop
	6150	$P6 = P5 - DP56$	Calculate cooling air outlet pressure
	6160	$T6 = \frac{(V5A)T6A + (V5 - V5A)T5}{V5}$	Calculate cooling air out temperature
	6170	IF $V1 \leq 62$ THEN $PWRCTB = 2.8V + 153.8$	
	6180	IF $62 < V1 \leq 65$ THEN $PWRCTB = 40V1 - 2150$	Calculate cathode air blower power
	6190	IF $65 < V1 \leq 70$ THEN $PWRCTB = -34V + 2660$	

Table 2 - continued

Symbol	Program Line Numbers	Description	Comments
	6200	$T11 = T2 + \frac{PWRCTB(U3)}{V1 \cdot CPA}$	
	6210	$V11 = V2$	Define stream after cathode blower
	6220	$P11 = P8$	
	6240-6250	IF $V5 - V5MIN < 0.001(V5MIN)$ THEN $PWRCLB = 0$; $DP1213 = C12132(V5)^2$ AND BRANCH	Check if cooling blower is off
	6260	$DP1213 = C12132 (V5MIN)^2$	Calculate cooling blower power
	6270	$TR = (\frac{DP78}{1.869} + 0.05)/1.3$	
	6280	$TR = TR^{(0.128 + 0.102(\frac{DP78}{1.869}))}$	
	6290	$PWH = 410 - 0.00396 (V5 - 368)^2$	
	6300	$PWL = 410 - 0.00178 (V5 - 306)^2$	
	6310	$PWRCLB = TR (PWH) + (1 - TR) (PWL)$	
	6330	$P12 = P8 + DP1213$	Define cooling blower exit stream
	6340	$T12 = T6 + \frac{PWRCTB(U3)}{V5 (CPA)}$	
	6350	$T13 = T12$	
	6360	$V12 = V5$	
	6370	$P13 = P8$	
	6380	$V13 = V5$	

Table 2 - continued

Symbol	Program Line Numbers	Description	Comments
C-24	6390	$V8 = V10 + V2 + V5$	Calculate plenum exit conditions
	6400	$VW8 = VW7 + VW2 - VW1$	
	6410	$VC8 = VC7 - VC4$	
	6420	$PC8 = \frac{VC8}{V8} P8$	
	6430	$VN8 = VN7$	
	6440	$PN8 = \frac{VN8}{V8} P8$	
	6450	$VO8 = VO7 - \frac{1}{2}(VH3 - VH4)$	
	6460	$PW8 = \frac{VW8}{V8} P8$	
	6470	$DW8 = DEWT (PW8)$	
	6480	$T8 = \frac{T11(V11) + T13(V13)}{V8} + \frac{T7(V10) + (POWER \frac{U3}{CPA})}{V8}$	
	6490	$RH8 = \frac{100 \times PW8}{PHTO (T8)}$	
	6500	IF (KBASE = 3) RETURN	
	6510	$AV7 = \frac{V7(T7 + 460)}{P7} \frac{760}{530}$	
	6520	$AV1 = V1 (AV7/V7)$	
	6530	$AV2 = \frac{V2(T2 + 460)}{P2} \times 1.434$	

Table 2 - continued

Symbol	Program Line Numbers	Description	Comments
	6540	$AV11 = \frac{V11(T11 + 460)}{P11} \quad (1.434)$	
	6550	$AV9 = \frac{V9(T9 + 460)}{P9} \quad (1.434)$	
	6560	$AV3 = \frac{V3(T3 + 460)}{P3} \quad (1.434)$	
	6570	$AV4 = \frac{V4(T4 + 460)}{P4} \quad (1.434)$	
	6580	$AV5 = V5 \quad AV7/V7$	Calculate actual stream flow rates
	6590	$AV6 = \frac{V6(T6 + 460)}{P6} \quad (1.434)$	
	6600	$V6A = V5A$	
	6610	$AV6A = \frac{V6A(T6A + 460)}{P6} \quad (1.434)$	
	6620	$AV12 = \frac{V12(T12 + 460)}{P12} \quad (1.434)$	
	6630	$AV13 = \frac{V13(T13 + 460)}{P13} \quad (1.434)$	
	6640	$AV10EX = \frac{V10(T7 + 460)}{P8} \quad (1.434)$	
	6650	$AV8 = \frac{V8(T8 + 460)}{P8} \quad (1.434)$	
	6690	$PWRTOT = PWRPC + PWREC + PWRCLE + PWRCTB + PWRDAU$	
	6700	$HTTOT = HEATLD + U3(PWRTOT + POWER)$	
	6710	$PWRWGT = PWPEN(PWRTOT)$	Calculate equivalent weight penalty
	6720	$HTWGT = HTPEN(HTTOT)$	
	6730	$H2OWGT = H2OPEN(WPROD)$	

Table 2 - continued



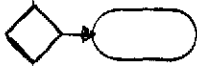


<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
	6740	OXWGT = OXPEN(OCON)	
	6750	EQWGT = PWRWGT + HTWGT + H ₂ OWGT + OXWGT + HRDWGT	
	6760	IF (KBASE = 4) RETURN	
	6770-7510	WRITE OUT ALL OUTPUTS	
	7520	RETURN	

TABLE 3 WATER VAPOR PRESSURE FUNCTION

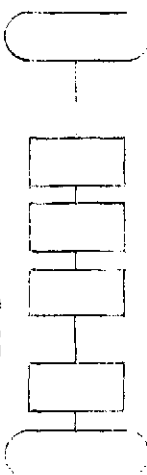
<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
	7550	FUNCTION PHTO(TF)	The input parameter is the Fahrenheit dew point temperature. The output parameter is p_{H_2O} , in millimeters of mercury.
	7560-7570		Initialize constants A-G.
	7580	$TC = (TF - 32) \cdot 1.8$	Calculate Centigrade dew point temperature.
	7590	$X = 374.11 - TC$	Calculate the temperature span from the dew point to the critical temperature.
	7600	$PHTO = 10^{(EE - \frac{X}{TC+F} \times \frac{A+BX+CX^3}{1+DX})}$	Calculate water vapor pressure
	7610	RETURN	

TABLE 4 DEW POINT TEMPERATURE FUNCTION

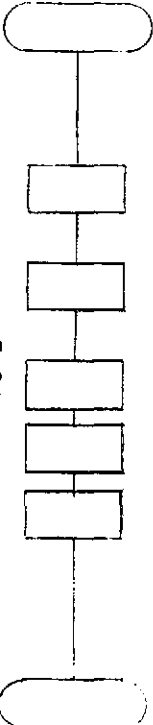
<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
 C-28	7640	FUNCTION DEWT(P)	The input parameter P is the water vapor pressure in millimeters of mercury. The output parameter DEWT is the Fahrenheit dew point temperature
	7650	EXTERNAL ROOT, PHTO	Functions ROOT and PHTO are used by function DEWT
	7660	X=ALOG(P)	Calculate two trial values for the dew point temperature
	7670	$TA = -2.4 + 20.25X + 1.522X^2$	
	7680	TB=TA + 0.1	
	4890	DEWT=ROOT(TA,TB,PHTO,P, 0.005, 0.005, 5)	Function ROOT will call function PHTO starting with dew points equal to TA and TB until the water vapor pressure is equal to P with temperature and vapor pressure tolerances of point .005 but not exceeding five trials.
	7700	RETURN	

TABLE 5 TRANSFER INDEX FUNCTION

Symbol	Program Line Numbers	Description	Comments
C-29	7730	FUNCTION TICOR(PC,AF,CD,DEL)	Input parameters are CO ₂ partial pressure in millimeters of mercury, cathode air flow in Cfm/cell, current density in Amp/Ft ² , and module temperature - inlet cathode air dew point temperature. The output parameter is TICOR in Lb CO ₂ /Lb O ₂ .
	7740-7810		Initialize the correlation parameters in array S.
	7820	P=AMIN1(PC,10)	pCO ₂ should not exceed 10.
	7830	$PA = PC \left(\frac{AF}{.44} \right)^{(1+0.84P)^{-0.84P}}$	PA is the effective inlet pCO ₂ corrected for nonbaseline cathode air flow.
	7840	$J = \frac{CD}{5} - 1$	Calculate the J index which corresponds to current density.
	7850	IF(J < 1)J=1	For current densities less than 10 ASF, extrapolate from 15 and 10 ASF.
	7860	$TI1 = \sum_{i=1}^5 S_{ij} PA^i$	Calculate TI at the current density just below the actual current density.
	7870	IF (J < 7) BRANCH	Current density should not exceed 40 ASF,
	7880	TICOR = TI1	
	7900	J = J + 1	Calculate TI at the current density just above the actual current density
	7910	$TI2 = \sum_{i=1}^5 S_{ij} PA^i$	
	7920	AII=J	Interpolate between the two current densities.

-continued-

Table 5 - continued


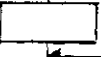
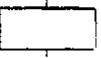
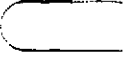
<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
	7930	$TERP = \frac{CD}{5} - AII$	
	7940	$TICOR = TI2 \times TERP + TI1(1 - TERP)$	
	7950	$TICOR = TICOR(1 + 0.03536(DEL - 18.33))$	Correct TI for moisture conditions.
	7960	RETURN	

TABLE 6 ROOT FUNCTION

<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
	7990	FUNCTION ROOT(X1,X2,YFCN,W,XTOL, YTOL,K)	Input parameters are the first and second trial root values, the function to be called which returns the function of X, the value of the function at the desired root, X tolerance, Y tolerance, and maximum trials. The output value, ROOT, is the value of X when the function equals W.
	8000-8010		Initialize common and external statements.
	8020	XA=X1	Isolate X1 and X2.
	8030	XB=X2	
	8040	FA=YFCN(XA) - W	Find the error values at XA and XB.
	8050	FB=YFCN(XB) - W	
	8060	BEGIN LOOP	
	8070	$XN = \frac{FA \cdot XB - FB \cdot XA}{FA - FB}$	Extrapolate from the previous two trial values.
	8080	FN=YFCN(XN) - W	Calculate the error at the next X value.
	8090-8100	IF (FN < YTOL and XN-XB < XTOL) BRANCH	BRANCH when the X and Y values are within tolerance.
	8110-8130	IF(Kth TIME THRU LOOP) DUMP VARIABLES & PRINT MESSAGE "NONCONVERGENCE IN LOOP"	If the root has not been found within K trials, print a message.
	8140	XA=XB	Drop the oldest trial value and add the new trial value.

-continued-

Table 6 - continued



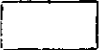




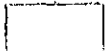



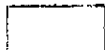
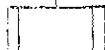
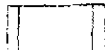










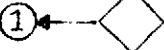
<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
	8150	XB=XN	
	8160	FA=FB	
	8170	FB=FN	
	8180	IF(<Kth TIME THRU LOOP) BRANCH	
	5260	ROOT=XN	The root of the function returned is the latest trial value.
	8190	RETURN	

TABLE 7 MODULE TEMPERATURE SUBROUTINE

<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
	8220	SUBROUTINE TDRIFT	Subroutine TDRIFT calculates the module temperature when the cooling air flow rate is specified. All inputs are through common storage. All outputs except P2 are also through common storage.
	8230-8280		Initialize type, common, and external statements.
	8290	$ENTHPR = V1 \cdot CPA \cdot T1 + V3 \cdot CPH \cdot T3$	Calculate enthalpy entering the modules in the cathode air and inlet hydrogen streams.
	8300	$T2HIGH = \frac{ENTHPR + .99 \cdot HEATLD}{V1 \cdot CPA + V3 \cdot CPH}$	Calculate maximum possible module temperature. This is the temperature the module would rise to with no cooling air.
	8310	$T2LOW = \frac{ENTHPR + V5A \cdot CPA \cdot T5 + HEATLD}{V1 \cdot CPA + V3 \cdot CPA + V5A \cdot CPA}$	Calculate the minimum module temperature which would occur with no heat transfer resistance.
	8320	$T2 = T2HIGH$	Call subroutine ERT to determine values of the heat transfer coefficient and the cooling fin efficiency, neither of which depends upon module temperature but only upon cooling air flow rate which is constant when subroutine TDRIFT is called.
	8330	$DUMMY = ERT(V5A/N)$	
	8340	$T2 = \text{ROOT}(T2HIGH, T2LOW, ERT1, 0,$	Start with trial values T2HIGH and T2LOW and use function ERT1 to find the module temperature which yields a heat balance for the specified cooling air flow rate.
	8350	RETURN	

C-33

TABLE 8 HEAT BALANCE FUNCTION WITH VARIABLE MODULE TEMPERATURE

Symbol	Program Line Numbers	Description	Comments
	8380	FUNCTION ERT1(T)	The input parameter is the module temperature. The output parameter, ERT1, is the difference between the available module cooling air temperature drop and the required module cooling air temperature drop.
	8390-8430		Initialize type, common statements.
	8440	$E = 0.729 - 0.221nI + 0.008I + 0.005(T-78)$	Calculate module voltage and heat load at the given temperature.
	8450	$HEATLD = N \cdot I \cdot (1.25 - E) \cdot 3.419$	
	8460	$DHA = V1(CPA)(T-T1)$	
	8470	$DHH = V3(CPH)(T-T3)$	
	8480	$DHC = HEATLD - DHA - DHH$	
	8490	$T6A = T5 + \frac{DHC}{V5A(CPA)}$	Calculate the outlet cooling air temperature from the inlet cooling air temperature and the enthalpy increase.
	8500	$DTREQ = DHC \left(0.376 + 3.876 \frac{HC \cdot ETA}{N} \right)$	
	8510	IF(T6A < T) BRANCH	If the cooling air temperature at the exit is less than the module temperature, then the log mean temperature difference can be calculated.

-continued-

Table 8 - continued

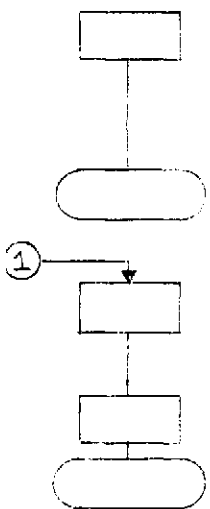
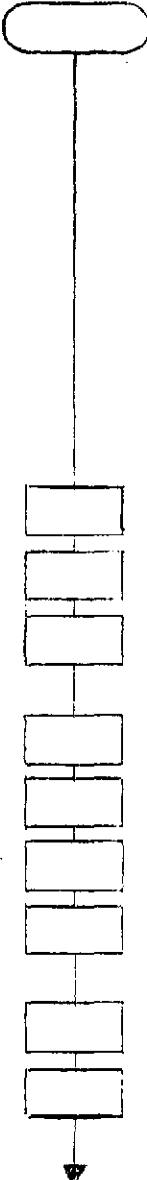



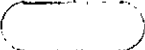


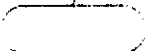
Symbol	Program Line Numbers	Description	Comments
 C-35	8520	ERT1 = -DTREQ	If it is not, then assume that the available temperature difference is zero and the error is equal to the required temperature difference.
	8530	RETURN	
	8540	$DTAVA = \frac{T6A - T5}{\ln \frac{T - T5}{T - T6A}}$	The available temperature drop is the log mean of the module cooling air temperature difference at the inlet and the outlet of the cooling air passages.
	8550	ERT1 = DTAVA - DTREQ	
	8560	RETURN	

TABLE 9 HEAT BALANCE FUNCTION WITH VARIABLE COOLING AIR FLOW RATE

Symbol	Program Line Numbers	Description	Comments
	8590	FUNCTION ERT(V)	The input parameter is the cooling air flow rate, Cfm/cell. The output parameter ERT is the difference between the available and required module-cooling air temperature differences. Inputs taken from common storage include the inlet cooling air and cathode air temperature, the cooling air heat load, the cooling air specific heat, the number of active cells, and the module temperature. Outputs through common storage include the heat transfer coefficient, the fin efficiency, the outlet cooling air temperature, the available temperature difference, and the required temperature difference.
	8600-8640		
	8650	IF $(V \leq 1) HC = 1.97V^{0.3333}$	Calculate the heat transfer coefficient.
	8660	IF $(1 < V < 2.9883) HC = 1.21 + 0.34V + 0.42V^2$	
	8670	IF $(2.9883 \leq V \leq 4) HC = 2V$	
	8680	IF $(4 < V) HC = 2.639016V^{.8}$	
	8690	ETA=1	Calculate the fin efficiency.
	8700	IF $(0.32194 < V \leq 24.72) ETA = 1.0644 - 0.1135V^{0.5}$	
	8710	IF $(24.72 \leq V) ETA = 2.486V^{.5}$	
	8720	$T6A = T5 + \frac{DHC}{V(CPA)N}$	

-continued-

Table 9 - continued

Symbol	Program Line Numbers	Description	Comments
	8730	$DTREQ = \frac{DHC}{N} \left(0.376 + \frac{3.876}{HC(ETA)} \right)$	Calculate the required temperature difference from the cooling air heat load, resistance in the fins, and resistance in the stagnant air film.
	8740	IF (T6A < T2) BRANCH	Branch and calculate the log mean temperature difference only if the outlet cooling air temperature is less than the module temperature.
	8750	ERT = -DTREQ	There is no available temperature difference. The error ERT is minus the required temperature difference.
	8760	RETURN	
	8770	$DTAVA = \frac{T6A - T5}{\ln \frac{T2 - T5}{T2 - T6A}}$	Log mean module cooling air temperature difference.
	8780	ERT = DTAVA - DTREQ	
	8790	RETURN	

C-37

TABLE 10 RANGE TEST SUBROUTINE

<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
	8820	SUBROUTINE T(VARNAM,VAR,BOT, TOP,I)	Subroutine input parameters are the variable, value, the lower and upper limits, and the out-of-range counter. The subroutine simply prints a message containing the first four parameters when the variable is out-of-range.
	8830	COMMON IOUT	The message is printed on output device IOUT.
	8840	IF (BOT \leq VAR \leq TOP) BRANCH	The subroutine ends immediately if the variable is in range.
	8840	RETURN	
	8850	WRITE, VARNAM, VAR, BOT, TOP	
	8860	I=I+1	
	8870	RETURN	

TABLE 11 MODE B CURRENT AND CATHODE AIR FLOW SUBROUTINE














<u>Symbol</u>	<u>Program Line Numbers</u>	<u>Description</u>	<u>Comments</u>
	8910	SUBROUTINE BMODE	Subroutine BMODE takes the cabin $p\text{CO}_2$ and calculates the current and the cathode air flow based on BK, the Mode B parameters.
	8920-8940		Initialize type and common statements.
	8950	$I = \text{BK}(1)$	Calculate current.
	8960	IF ($\text{PCO} \leq \text{BK}(2)$) BRANCH	
	8970	$I = \text{BK}(4)$	
	8980	IF ($\text{PCO} \geq \text{BK}(3)$) BRANCH	
	8990	$I = \text{BK}(9) \cdot \text{PCO} + \text{BK}(10)$	
	9000	$V1 = \text{BK}(5)$	Calculate cathode air flow.
	9010	IF ($\text{PCO} \leq \text{BK}(6)$) BRANCH	
	9020	$V1 = \text{BK}(8)$	
	9030	IF ($\text{PCO} \geq \text{BK}(7)$) BRANCH	
	9040	$V1 = \text{BK}(11) \cdot \text{PCO} + \text{BK}(12)$	
	9050	RETURN	

TABLE 12 CYCLIC PROGRAM LISTING

```

100$SAV
110C *** CYCLIC PROGRAM *** CS-6 MATH MODEL ***
120C
130$TTY,84
140$NDM
150 LOGICAL QFIN,QFOOT,QC02GT,QSUBS,QPRINT
160 REAL N,I,HEAD(150),CGEN(200),HDG(150),AO(150),TAB(150),AVG(150)
170 INTEGER INDEX(150),TMAX(200)
180 COMMON IOUT,CPA,CPH,N,V3,T5,T3,T1,BK(12),
1902POPSA,POOPSA,TO,VOLUME,P8PSA,T7,V7,
200&DW7,P4PSA,T9,V9SL,DW9,PWPEN,HTPEN,H2OPEN,OXPEN,NFLAG,
210&PC0,I,V1,HEATLD,DHC,DHA,DHH,DTREQ,DTAVA,E,
220&HC,ETA,T2,V5A,T6A,DELT1,V9MSL,V7M1,V5MIN,V5,
230&DUM(5),YA,YB,YC,SLOPEC,CO2GEN,
240&V5INP,V10,COR34,DP34,P3,P3PSA,COR93,DP93,P9,P9PSA,
250&DP78,P7,P7PSA,DP12,P1,P2,CURDEN,DELT1E,PC1,TI,
260&OCON,CTRANS,HCON,WPROD,VC4,PW9,PW3,VH3,VH4,PW1,
270&VW1,VW3,VWPROD,VW2,P00,P07,PN1,VN1,VO1,VC1,
280&V02,VC2,V2,PW2,DW2,DDP1,DDP2,DPTDAV,DELT1P,T2P,
290&VC7,VW7,VO7,VN7,RH7,FC1,FW1,PH3,FH3,EMOD,
300&POWER,TE,PC2,FC2,FW2,RH2,DW4,PW4,VW4,V4,
310&V4SL,VC4SL,VH4SL,FC4,FH4,FW4,F4,CHWRT0,HCVRT0,DP56,
320&P6,T6,PWRCTB,T11,DP1213,PWRCLB,P12,T12,V8,VW8,
330&VC8,PC8,VN8,PN8,VO8,PW8,DW8,T8,RH8,AV1,
340&AV2,AV3,AV4,AV5,AV6,AV6A,AV7,AV8,AV9,AV10EX,
350&AV11,AV12,AV13,PWRTOT,HTTOT,PWRWGT,HTWGT,H2OWGT,OXWGT,EWGT
360 EQUIVALENCE(AO(1),PC0)
370 DATA IOUT,NSTEPS,(TMAX(MN),CGEN(MN),MN=1,21)/1,21,
380&405,.3530, 420,.4118, 435,.4706, 450,.5295, 465,.5687, 480,.7060,
390&705,.7452, 720,.6079, 780,.5295, 840,.5687, 900,.6667, 1020,.7452,
400&1080,.6667, 1140,.5295, 1200,.5687, 1290,.6471, 1320,.6079,
410&1365,.5295, 1380,.4706, 1395,.4118, 1440,.3530/
420 DATA HEAD/
430&" PC0"," I"," V1","HEATLD"," DHC",
440&" DHA"," DHH"," DTREQ"," DTAVA"," E",
450&" HC"," ETA"," T2"," V5A"," T6A",
460&" DELT1"," V9MSL"," V7M1"," V5MIN"," V5",
470&" DUM1"," DUM2"," DUM3"," DUM4"," DUM5",
480&" YA"," YB"," YC","SLOPEC","CO2GEN",
490&" V5INP"," V10"," COR34"," DP34"," P3",
500&" P3PSA"," COR93"," DP93"," P9"," P9PSA",
510&" DP78"," P7"," P7PSA"," DP12"," P1",
520&" P2","CURDEN","DELT1E"," PC1"," TI",
530&" OCON","CTRANS"," HCON"," WPROD"," VC4",
540&" PW9"," PW3"," VH3"," VH4"," PW1",
550&" VW1"," VW3","VWPROD"," VW2"," P00",
560&" P07"," PN1"," VN1"," VO1"," VC1",
570&" V02"," VC2"," V2"," PW2"," DW2",
580&" BDP1"," DDP2","DPTDAV","DELT1P"," T2P",
590&" VC7"," VW7"," VO7"," VN7"," RH7",

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continued-

Table 12 - continued

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600&" FC1"," FW1"," PH3"," FH3"," EMOD",
610&" POWER"," TE"," PC2"," FC2"," FW2",
620&" RH2"," DW4"," PW4"," VW4"," V4",
630&" V4SL"," VC4SL"," VH4SL"," FC4"," FH4",
640&" FW4"," F4","CHWRT0","HCVRT0"," DP56",
650&" P6"," T6","PWRCTB"," T11","DP1213",
660&"PWRCLB"," P12"," T12"," V8"," VW8",
670&" VC8"," PC8"," VN8"," PN8"," VO8",
680&" PW8"," DW8"," T8"," RH8"," AV1",
690&" AV2"," AV3"," AV4"," AV5"," AV6",
700&" AV6A"," AV7"," AV8"," AV9","AV10EX",
710&" AV11"," AV12"," AV13","PWRTOT"," HTTOT",
720&"PWRWGT"," HTWGT","H2OWGT"," OXWGT"," EQWGT"/
730C
740C DETERMINE I/O DEVICES:
750C
760 PRINT,"FILE INPUT (T OR F)",,*
770 READ,QFIN
780 INP=50
790 IF(QFIN)INP=2
800 IF(QFIN)CALL OPENF(2,"MATHIN")
810 PRINT,"FILE OUTPUT (T OR F)",,*
820 READ,QFOUT
830 IF(.NOT.QFOUT)IOUT=66
840 GOT06
850 99 PRINT," END OF INPUT DATA FILE"
860 CALL EXIT
870C
880C IF OUTPUT IS TO FILE, OBTAIN FILE NAME:
890C
900 IIF(.NOT.QFOUT)GOT06
910 IF(.NOT.QFIN)PRINT,"FILE FOR OUTPUT",,*
920 READ(INP,48,END=99)FNAME
930 48 FORMAT(14A6)
940C
950C IF THE FILE NAME IS "SAME",KEEP FILE OPEN FOR MORE OUTPUT,
960C OTHERWISE ASSIGN THE NAME AND CLOSE THE FILE:
970C
980 IF(FNAME.NE."SAME")CALL CLOSEF(1,FNAME,7)
990C
1000C READ AND WRITE PROBLEM IDENTIFIER:
1010C
1020 GWRITE(IOUT;4)
1030 4 FORMAT(//////)
1040 IF(.NOT.QFIN)PRINT,"PROBLEM IDENTIFIER:"
1050 READ(INP,48,END=99)(HDG(J),J=1,14)
1060 IF(QFIN)WRITE(IOUT;48)(HDG(J),J=1,14)
1070C
1080C INPUT AND OUTPUT NEW CO2 GENERATION TABLE IF DESIRED:
1090C

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continued-

Table 12 - continued

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1100 IF(.NOT.QFIN)PRINT,"NEW CO2 GENERATION TABLE(T OR F)",!*
1110 READ(INP,,END=99)QCO2GT
1120 IF(QCO2GT)READ(INP,,END=99)NSTEPS,(TMAX(MN),CGEN(MN),MN=1,NSTEPS)
1130 IF(QCO2GT)WRITE(IOUT;100)NSTEPS,(TMAX(MN),CGEN(MN),MN=1,NSTEPS)
1140 100 FORMAT(/" CO2 GENERATION RATE TABLE:"/" NUMBER OF STEPS=",I3//
1150&" ENDING          CO2"/"      TIME GENERATION"/" MINUTES          LB/HR"/
1160&(F8.0,F11.4))
1170C
1180C   INPUT FOR BASE, MODE B, NO. OF DAYS, SIZES OF TIME INTERVALS
1190C   FOR INTEGRATION AND PRINTING:
1200C
1210 IF(.NOT.QFIN)PRINT,"INPUT DATA",!*
1220 READ(INP,,END=99)POPSA,PCO,POOPSA,TO,VOLUME,PBPSA,T7,V7,DW7,P4PSA,T9,V9SL,DW9,
1230&N,I,DELT1,V1,PWPEN,HTPEN,H2OPEN,OXPEN,KMODE,NFLAG,(BK(MN),MN=1,8),DAYS,DT,DPRINT
1240C
1250C   DETERMINE WHETHER BASE OUTPUT IS TO BE PRINTED AND
1260C   INPUT THE SUBSCRIPTS OF THE DESIRED CYCLIC TABLE OUTPUT ITEMS:
1270C
1280 IF(.NOT.QFIN)PRINT,"PRINT BASE OUTPUT(T OR F)",!*
1290 READ(INP,,END=99)QPRINT
1300 KBASE=4
1310 IF(QPRINT)KBASE=5
1320 IF(.NOT.QFIN)PRINT,"NEW CYCLIC OUTPUT SUBSCRIPTS(T OR F)",!*
1330 READ(INP,,END=99)QSUBS
1340 IF(QSUBS)READ(INP,,END=99)NDEX,(INDEX(MN),MN=1,NDEX)
1350 IF(QFOOT)PRINT," START PROBLEM"
1360C
1370C   CALC. SLOPES AND INTERCEPTS FOR MODE B CURRENT AND AIRFLOW CURVES:
1380C
1390 BK(9)=(BK(1)-BK(4))/(BK(2)-BK(3))
1400 BK(10)=BK(1)-BK(9)*BK(2)
1410 BK(11)=(BK(5)-BK(8))/(BK(6)-BK(7))
1420 BK(12)=BK(5)-BK(11)*BK(6)
1430C
1440C   IF MODE B IS IN EFFECT, DETERMINE INITIAL VALUES OF I AND V1
1450C   BY CALLING SUBROUTINE "BMODE":
1460C
1470 IF(KMODE.EQ.1)CALL BMODE
1480C
1490C   INPUT DATA PLAYBACK:
1500C
1510 WRITE(IOUT;230)
1520 230FORMAT(" *****INPUT DATA*****")
1530 WRITE(IOUT;1017)
1540 1017FORMAT(" CABIN ATMOSPHERE:")
1550 944 FORMAT(5X,A6,G10.4,3(" ! ",A6,G10.4))
1560 WRITE(IOUT;944)"POPSA",POPSA,"PCO",PCO,"POOPSA",POOPSA,"TO ",TO,"VOLUME",VOLUME
1570 WRITE(IOUT;1032)
1580 1032FORMAT(" PROCESS AIR OUTLET/INLET:")
1590 WRITE(IOUT;944)"P8PSA",P8PSA,"T7 ",T7,"V7 ",V7,"DW7",DW7

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Table 12 - continued

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1600 WRITE(IOUT;1031)
1610 1031FORMAT(" H2 OUTLET/INLET:")
1620 WRITE(IOUT;944)"P4PSA",P4PSA,"T9 ",T9,"V9SL",V9SL,"DW9",DW9
1630 WRITE(IOUT;1020)
1640 1020FORMAT(" MODULES:")
1650 WRITE(IOUT;944)"N ",N,"I ",I,"DELT1",DELT1,"V1 ",V1
1660 WRITE(IOUT;1021)
1670 1021FORMAT(" PENALTY WEIGHT FACTORS:")
1680 WRITE(IOUT;944)"PWPEN",PWPEN,"HTPEN",HTPEN,"H2OPEN",H2OPEN,
1690"OXPEN",OXPEN
1700 WRITE(IOUT;1022)
1710 1022 FORMAT(" CONTROL:")
1720 WRITE(IOUT;944)"KMODE",KMODE,"NFLAG",NFLAG
1730"IMIN",BK(1),"PCIMIN",BK(2),"PCIMAX",BK(3),"IMAX",BK(4),
1740"VMIN",BK(5),"PCVMIN",BK(6),"PCVMAX",BK(7),"VMAX",BK(8)
1750"DAYS",DAYS,"DT ",DT,"DPRINT",DPRINT
1760 WRITE(IOUT;4)
1770 WRITE(IOUT;220)
1780 220 FORMAT(" *****RESULTS*****")
1790C
1800C CHECK INPUTS:
1810C
1820 IR=0
1830 CALLT("POPSA ",POPSA,13.7,15.7,IR)
1840 CALLT("PCO",PCO,.0001,10.,IR)
1850 CALLT("POOPSA",POOPSA,2.,4.,IR)
1860 CALLT("TO ",TO,44.,80.,IR)
1870 CALLT("VOLUME",VOLUME,100.,100000.,IR)
1880 CALLT("P8PSA ",P8PSA,13.7,15.7,IR)
1890 CALLT("T7 ",T7,44.,80.,IR)
1900 CALLT("V7 ",V7,0.,600.,IR)
1910 CALLT("DW7 ",DW7,41.,70.,IR)
1920 CALLT("P4PSA ",P4PSA,14.8,21.2,IR)
1930 CALLT("T9 ",T9,65.,75.,IR)
1940 CALLT("V9SL ",V9SL,0.,18.,IR)
1950 CALLT("DW9 ",DW9,10.,75.,IR)
1960 CALLT("N ",N,90.,96.,IR)
1970 CALLT("I ",I,2.44,9.76,IR)
1980 CALLT("DELT1 ",DELT1,10.,25.,IR)
1990 CALLT("V1 ",V1,5.,76.8,IR)
2000 CALLT("PWPEN ",PWPEN,0.,2.,IR)
2010 CALLT("HTPEN ",HTPEN,0.,2.,IR)
2020 CALLT("H2OPEN",H2OPEN,0.,500.,IR)
2030 CALLT("OXPEN ",OXPEN,0.,3000.,IR)
2040 FLAG=NFLAG
2050 CALLT("NFLAG ",FLAG,0.,1.,IR)
2060 AMODE=KMODE
2070 CALLT("KMODE ",AMODE,0.,1.,IR)
2080 CALLT("IMIN",BK(1),2.44,9.76,IR)
2090 CALLT("PCIMIN",BK(2),.0001,10.,IR)

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continued-

Table 12 - continued

```
2100 CALLT("PCIMAX",BK(3),.0001,10.,IR)
2110 CALLT("IMAX",BK(4),2.44,9.76,IR)
2120 CALLT("VMIN",BK(5),5.,76.8,IR)
2130 CALLT("PCVMIN",BK(6),.0001,10.,IR)
2140 CALLT("PCVMAX",BK(7),.0001,10.,IR)
2150 CALLT("VMAX",BK(8),5.,76.8,IR)
2160 CALLT("DAYS",DAYS,0.,10.,IR)
2170 CALLT("DT ",DT,1.,15.,IR)
2180 CALLT("DPRINT",DPRINT,1.,100.,IR)
2190 IF(IR.GT.0)GOTO1
2200C
2210C   PRINT FULL BASE PROGRAM OUTPUT IF DESIRED:
2220C
2230 CALL BASE(KMODE,KBASE,1,KERROR)
2240 IF(KERROR.NE.0 .OR. DAYS.EQ.0.)GOTO1
2250C
2260C   INITIALIZE CONSTANTS:
2270C
2280 NDT=DT
2290 NDAY=0
2300 MINCYC=TMAX(NSTEPS)
2310 NDAY=NDAYS
2320 NPRINT=DPRINT
2330 US=(T0+460.)*386.72*760./(530.*VOLUME*60.*44.01)
2340 MAXDEX=0
2350 DO 110 MN=1,NDEX
2360 IN=INDEX(MN)
2370 HDG(MN)=HEAD(IN)
2380 110 IF(IN.GT.MAXDEX)MAXDEX=IN
2390 KBASE=1
2400 IF(MAXDEX.GT.52)KBASE=2
2410 IF(MAXDEX.GT.78)KBASE=3
2420 IF(MAXDEX.GT.129)KBASE=4
2430C
2440C   START A NEW CYCLE (DAY):
2450C
2460 7800CCONTINUE
2470 QPRINT=.TRUE.
2480 NT=0
2490 DO 725 MN=1,NDEX
2500 725AVG(MN)=0.
2510 NDAY=NDAY+1
2520 PCOI=PCO
2530 IGEN=1
2540 CO2GEN=CGEN(1)
2550C
2560C   PRINT CYCLIC TABLE HEADINGS:
2570C
2580 IF(QFOUT)PRINT,NDAY
2590 WRITE(IOUT;120)NDAY,(HDG(MN),MN=1,NDEX)
```

Table 12 - continued

```

2600 120FORMAT(///" *****DAY",I3," *****"/" TIME"/(7(5X,A6)))
2610 WRITE(IOUT;121)
2620 121FORMAT("/ *****"/)
2630 WRITE(IOUT;135)0.0
2640 CALL BASE(KMODE,KBASE,1,KERROR)
2650 IF(KERROR.NE.0)GOTO1
2660C
2670C PRINT A LINE IN THE TABLE:
2680C
2690 7900CCONTINUE
2700 IF(.NOT.QPRINT)GOTO8000
2710 DO 130 MN=1,NDEX
2720 IN=INDEX(MN)
2730 130 TAB(MN)=A0(IN)
2740 WRITE(IOUT;140)(TAB(MN),MN=1,NDEX)
2750 140FORMAT(7(G11.4))
2760C
2770C START A NEW CYCLE AT THE END OF THE CURRENT CYCLE
2780C UNLESS EITHER STEADY STATE HAS BEEN REACHED
2790C OR MAXIMUM NUMBER OF CYCLES HAS BEEN REACHED
2800C
2810 8000CCONTINUE
2820 IF(NT.LT.MINCYC)GOTO8100
2830 DO 726MN=1,NDEX
2840 726AVG(MN)=AVG(MN)*DT/MINCYC
2850 WRITE(IOUT;122)
2860 122FORMAT(" AVERAGES:")
2870 WRITE(IOUT;140)(AVG(MN),MN=1,NDEX)
2880 IF(NDAY.GE.NDAYS .OR. ABS((PCO-PCOI)/PCO).LE..0005)GOTO1
2890 GOTO7800
2900C
2910C INCREMENT TIME AND UPDATE CO2 GENERATION RATE
2920C
2930 8100CCONTINUE
2940 NT=NT+NDT
2950 QPRINT=MOD(NT,NPRINT).EQ.0
2960 IF(NT.GT.TMAX(IGEN))IGEN=IGEN+1
2970 CO2GEN=CGEN(IGEN)
2980C
2990C WRITE THE TIME:
3000C
3010 IF(.NOT.QPRINT)GOTO8200
3020 NHRS=NT/60
3030 NMIN=NT-NHRS*60
3040 WRITE(IOUT;135)NHRS,NMIN
3050 135FORMAT(1X,I2,":",I2)
3060C
3070C UPDATE CABIN CO2 PARTIAL PRESSURE
3080C
3090 8200 CONTINUE

```

Table 12 - continued

```

3100 XA=PCO
3110 SLOPEA=U5*(CO2GEN-CTTRANS)
3120 SLOPE=SLOPEA
3130 PCN=PCO+SLOPE*DT
3140 YA=XA-PCN
3150 XB=PCN
3160 PCO=PCN
3170 CALL BASE(KMODE,0,0,KERROR)
3180 IF(KERROR.NE.0)GOTO1
3190 SLOPEB=U5*(CO2GEN-CTTRANS)
3200 SLOPE=.5*(SLOPEA+SLOPEB)
3210 PCN=XA+SLOPE*DT
3220 YB=XB-PCN
3230 PCO=(YA*XB-YB*XA)/(YA-YB)
3240 KPRINT=0
3250 IF(QPRINT)KPRINT=1
3260C
3270C CALL BASE TO CALC. SYSTEM PARAMETERS AT NEW CABIN PCO2
3280C
3290 CALL BASE(KMODE,KBASE,KPRINT,KERROR)
3300 IF(KERROR.NE.0)GOTO1
3310 DO 728MN=1,NDEX
3320 IN=INDEX(MN)
3330 728AVG(MN)=AVG(MN)+A0(IN)
3340C CHECK ACCURACY OF INTEGRATION:
3350C
3360 SLOPEC=U5*(CO2GEN-CTTRANS)
3370 SLOPE=.5*(SLOPEA+SLOPEC)
3380 PCN=XA+SLOPE*DT
3390 YC=PCO-PCN
3400C YC IS THE INACCURACY IN PCO
3410 GOTO7900
3420 END
3430C
3440 SUBROUTINE BASE(KMODE,KBASE,KPRINT,KERROR)
3450C
3460C *** CS-6 MATH MODEL BASE PROGRAM ***
3470C
3480 REALN,I
3490 COMMONIOUT,CPA,CPH,N,V3,T5,T3,T1,BK(12),
3500&POPSA,POOPSA,T0,VOLUME,P8PSA,T7,V7,
3510&DW7,P4PSA,T9,V9SL,DW9,PWPEN,HTPEN,H2OPEN,OXPEN,NFLAG,
3520&PCO,I,V1,HEATLD,DHC,DHA,DHH,DTREQ,DTAVA,E,
3530&HC,ETA,T2,V5A,T6A,DELT1,V9MSL,V7M1,V5MIN,V5,
3540&DUM(5),YA,YB,YC,SLOPEC,CO2GEN,
3550&V5INP,V10,COR34,DP34,P3,P3PSA,COR93,DP93,P9,P9PSA,
3560&DP78,P7,P7PSA,DP12,P1,P2,CURDEN,DELT1E,PC1,TI,
3570&OCON,CTTRANS,HCON,WPROD,VC4,PW9,PW3,VH3,VH4,PW1,
3580&VW1,VW3,VWPROD,VW2,P00,P07,PN1,VN1,V01,VC1,
3590&V02,VC2,V2,PW2,DW2,DDP1,DDP2,DPTDAY,DELT1P,T2P,

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Table 12 - continued

```

3600&VC7,VW7,VO7,VN7,RH7,FC1,FW1,PH3,PH3,EMOD,
3610&POWER,TE,PC2,FC2,FW2,RH2,DW4,PW4,VW4,V4,
3620&V4SL,VC4SL,VH4SL,FC4,FH4,FW4,F4,CHWRTO,HCVRTO,DP56,
3630&P6,T6,PWRCTB,T11,DP1213,PWRCLB,P12,T12,V8,VW8,
3640&VC8,PC8,VN8,PN8,VO8,PW8,DW8,T8,RH8,AV1,
3650&AV2,AV3,AV4,AV5,AV6,AV6A,AV7,AV8,AV9,AV10EX,
3660&AV11,AV12,AV13,PWRTOT,HTTOT,PWRWGT,HTWGT,H2OWGT,OXWGT,EQWGT
3670 EXTERNAL PHTO,DEWT,TICOR,ROOT,TDRIFT,ERT1,ERT,BMODE
3680 DATA CPA,CPH/1.0765,1.0666/
3690&,U1,U2,U3,U4/51.7007,386.7,3.419,28.32/
3700&,C782,C562,C561,C12132/2.25E-5,1.303E-5,.0101,8.6118E-4/
3710&,C5132,C5131,QA/8.742E-4,.0101,8.517E-4/
3720&,HRDWGT,PWRPC,PWREC,PWRDAU/817.9,136.,45.,100./
3730 KERROR=0
3740 IF(KMODE+KBASE.EQ.0)GOTO 7700
3750 IF(KMODE.EQ.1)CALL BMODE
3760C
3770C CHECK FOR SUFFICIENT H2:
3780C
3790 V9MSL=1.3*N*I*7.508E-3
3800 IF(V9SL.GE.V9MSL)GOTO1213
3810 WRITE(IOUT;213)V9MSL
3820 213 FORMAT(" INSUFFICIENT H2.",G10.4," SLPM IS REQUIRED")
3830 KERROR=1
3840 RETURN
3850 1213 CONTINUE
3860C
3870C CHECK CATHODE AIR CAPACITY:
3880C
3890 IF(V1.LE.70)GOTO9001
3900 V1=70.
3910 WRITE(IOUT;9000)
3920 9000FORMAT(" V1 HAS BEEN CHANGED TO 70 SCFM, BLOWER CAPACITY.")
3930 9001 CONTINUE
3940C
3950C CALC. COOLING AIR FLOW WITH COOLING BLOWERS OFF:
3960C
3970 V7M1=V7-V1
3980 QB=C5131+2.*C782*V7M1
3990 QC=C782*V7M1**2
4000 V5MIN=(-QB+SQRT(QB*QB+4.*QA*QC))/(2.*QA)
4010C
4020C CALC. COOLING AIR HEAT LOAD, ETC. FOR INPUT MODULE TEMP:
4030C
4040 DW1=DW7
4050 T2=DW1+DELT1
4060 T2INP=T2
4070 E=.729-.22*ALOG(I)+.008*I+.005*(T2-78.)
4080 HEATLD=N*I*(1.25-E)*U3
4090 T1=T7

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continued-

Table 12 - continued

```
4100 T3=T9
4110 V3=V9SL/U4
4120 T5=T1
4130 DHA=V1*CPA*(T2-T1)
4140 DHH=V3*CPH*(T2-T3)
4150 DHC=HEATLD-DHA-DHH
4160C
4170C   CHECK NEED FOR COOLING:
4180C
4190 IF(DHC.GT.0)GOTO898
4200C
4210C   CALC. NEW MODULE TEMP IF COOLING BLOWERS ARE OFF:
4220C
4230 888 CONTINUE
4240 V5=V5MIN
4250 V5A=N*V5MIN/96.
4260 CALL TDRIFT
4270 DROP=T2INP-T2
4280 IF(DROP.LE.3.)GOTO766
4290 IF(KPRINT.EQ.0)GOTO766
4300 WRITE(IOUT;469)DROP,T2INP,T2
4310 469 FORMAT(" COOLING BLOWERS ARE OFF."/" MODULE TEMPERATURE FALLS",
4320&F6.2,"F BELOW THE DESIRED",F6.2,"F TO",F6.2,"F.")
4330 GOTO766
4340C
4350C   CHECK THAT MODULE TEMP IS HIGH ENOUGH TO TRANSFER HEAT
4360C   AT LEAST TO COOLING FIN ROOTS:
4370C
4380 898 CONTINUE
4390 IF(T2-T5.GE..376*DHC/N)GOTO765
4400C
4410C   CALC. NEW MODULE TEMP IF COOLING BLOWERS ARE ON FULL:
4420C
4430 886 CONTINUE
4440 V5=440.
4450 V5A=V5*N/96.
4460 CALL TDRIFT
4470 RISE=T2-T2INP
4480 IF(RISE.LE.3)GOTO766
4490 IF(KPRINT.EQ.0)GOTO766
4500 WRITE(IOUT;479)RISE,T2INP,T2
4510 479 FORMAT(" COOLING BLOWERS ARE ON FULL."/" MODULE TEMPERATURE RISES",
4520&F6.2,"F ABOVE THE DESIRED",F6.2,"F TO",F6.2,"F.")
4530 GOTO766
4540C
4550C   CALC. COOLING AIR FLOW FOR INPUT MODULE TEMPERATURE:
4560C
4570 765 CONTINUE
4580 VA=1.01*DHC/(CPA*N*(T2-T5))
4590 VB=2.*VA
```

Table 12/ - continued

```

4600 V5A=N*ROOT(VA,VB,ERT,0...005,.001,20)
4610 V5=96.*V5A/N
4620 V5INP=V5
4630C
4640C ARE COOLING BLOWERS OUT OF RANGE:
4650C
4660 IF(V5.LT.V5MIN)GOTO888
4670 IF(V5.GT.440.)GOTO886
4680C
4690C MODULE HEAT BALANCE IS MAINTAINED WITH COOLING BLOWERS IN RANGE:
4700C
4710 766 CONTINUE
4720 V10=V7-V1-V5
4730C
4740C CHECK PLENUM BYPASS FLOW:
4750C
4760 IF(V10.GE..05*V7)GOTO244
4770 IF(KPRINT.EQ.0)GOTO244
4780 WRITE(IOUT;242)
4790 WRITE(IOUT;944)"V10",V10
4800 242FORMAT(" INSUFFICIENT INLET PROCESS AIR TO ",
4810"PREVENT BACKMIXING THROUGH PLENUM BYPASS.")
4820 KERROR=2
4830 RETURN
4840C
4850C CALC. STREAM PARAMETERS REQUIRED FOR MOISTURE BALANCE CHECKS:
4860C
4870 244 CONTINUE
4880 IF(KBASE.EQ.0)GOTO7107
4890 COR34=(14.1/P4PSA)**.8
4900 P4=P4PSA*U1
4910 V3SL=V9SL
4920 DP34=.3822*COR34*V3SL
4930 IF(V3SL.GT.22.)DP34=COR34*(8.3183+.4187*(V3SL-21.5801)**1.75)
4940 P3=P4+DP34
4950 P3PSA=P3/U1
4960 COR93=(14.1/P3PSA)**.8
4970 DP93=COR93*10.64*V3SL
4980 IF(V3SL.GT.6.2)DP93=COR93*(35.14*V3SL-195.25+EXP(7.75-.6537*V3SL))
4990 P9=P3+DP93
5000 P9PSA=P9/U1
5010 DP78=C782*V10*V10
5020 P8=P8PSA*U1
5030 P7=P8+DP78
5040 P7PSA=P7/U1
5050 DP12=V1*(.001903*V1+.04877)
5060 P1=P7
5070 P2=P1-DP12
5080 7107CURDEN=I/.244
5090 DELTIE=T2-DW1

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continued-

Table 12 - continued

```

5100 7700 CONTINUE
5110 PC1=PC0*P7PSA/POPSA
5120 TI=TICOR(PC1,V1/96.,CURDEN,DELTIME)
5130 OCON=6.5803E-4*N*I
5140 CTRANS=TI*OCON
5150 IF(KBASE.LE.1)RETURN
5160 HCON=OCON*2.016/16.
5170 WPROD=OCON+HCON
5180 VC4=CTrans*U2/(44.01*60.)
5190 PW9=PHTO(DW9)
5200 PW3=P3*PW9/P9
5210 VH3=V3*(1.-PW3/P3)
5220 VH4=VH3-HCON*U2/(2.016*60.)
5230C TRIAL VALUE OF H2+CO2 OUTLET WATER VAPOR PRESSURE:
5240 PW4=PHTO(T2-6.)
5250 VW4=PW4*(VC4+VH4)/(P4-PW4)
5260 DW1=DW7
5270 PW1=PHTO(DW1)
5280 VW1=V1*PW1/P1
5290 VW3=V3-VH3
5300 VWPROD=WPROD*U2/(18.01*60.)
5310 VW2=VW1+VW3-VW4+VWPROD
5320 PO0=PO0PSA*U1
5330 PO7=PO0*P7PSA/POPSA
5340 PO1=PO7
5350 PN1=P1-PO1-PW1-PC1
5360 VN1=V1*PN1/P1
5370 VO1=V1*PO1/P1
5380 VC1=V1*PC1/P1
5390 VN2=VN1
5400 VO2=VO1-OCON*U2/(32.*60.)
5410 VC2=VC1-VC4
5420 V2=VO2+VN2+VW2+VC2
5430 PW2=VW2*P2/V2
5440 DW2=DEWT(PW2)
5450C
5460C CHECK MODULE MOISTURE BALANCE:
5470C
5480 DDP1=T1-DW1
5490 DDP2=T2-DW2
5500 IF(ABS(DDP1-11.25).LE.1.75 .AND. ABS(DDP2-11.25).LE.1.75)GOTO30
5510 IF(DDP1.LT.4.)GOTO1210
5520 IF(DDP1.GT.14.)GOTO1210
5530 IF(DDP2.LT.7.)GOTO1211
5540 IF(DDP2.GT.19.)GOTO1211
5550 DPTDAV=.5*(DDP1+DDP2)
5560 IF(ABS(DPTDAV-11.).LE.1.5 .AND. (DDP2.GE.13. .OR. DPTDAV.GE.10.))GOTO30
5570 IF(KPRINT.EQ.1)WRITE(IOUT;654)
5580 654FORMAT(" AVERAGE CATHODE AIR DEWPOINT DEPRESSION OUT OF RANGE.")
5590 28 IF(KPRINT.EQ.1)WRITE(IOUT;543)

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continued-

Table 12 - continued

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5600 543FORMAT(" ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.")
5610 IF(NFLAG.EQ.0)GOTO30
5620 KERROR=3
5630 RETURN
5640 1210 IF(KPRINT.EQ.1)WRITE(IOUT;432)
5650 432FORMAT(" INLET CATHODE AIR DEWPOINT DEPRESSION OUT OF RANGE.")
5660 GOTO28
5670 1211 IF(KPRINT.EQ.1)WRITE(IOUT;321)
5680 321FORMAT(" OUTLET CATHODE AIR DEWPOINT DEPRESSION OUT OF RANGE.")
5690 GOTO28
5700C
5710C  COMPLETE ALL STREAM DEFINITIONS:
5720C
5730 30 CONTINUE
5740 IF(KBASE.EQ.2)RETURN
5750 DELT1P=22.-T1+DW2
5760 T2P=DW1+DELT1P
5770 PW7=PW1
5780 PN7=PN1
5790 PC7=PC1
5800 VC7=PC7*V7/P7
5810 VW7=PW7*V7/P7
5820 PO7=PO1
5830 VO7=PO7*V7/P7
5840 VN7=PN7*V7/P7
5850 RH7=100.*PW7/PHTO(T7)
5860 FC1=VC1*44.01*60./U2
5870 FW1=VW1*18.01*60./U2
5880 RH1=RH7
5890 PH3=P3-PW3
5900 FH3=VH3*2.016*60./U2
5910 EMOD=16.*E
5920 POWER=N*I*E
5930 TE=TI/.0275
5940 PC2=VC2*P2/V2
5950 FC2=FC1-CTrans
5960 FW2=VW2*18.01*60./U2
5970 RH2=100.*PW2/PHTO(T2)
5980 T4=T2
5990 V9=V3
6000 DW4=.77*(DW1+DW2)/2. + .23*T2
6010 PW4=PHTO(DW4)
6020 VW4=PW4*(VH4+VC4)/(P4-PW4)
6030 V4=VH4+VC4+VW4
6040 V4SL=V4*U4
6050 VC4SL=VC4*U4
6060 VH4SL=VH4*U4
6070 FC4=CTrans
6080 FH4=VH4*2.016*60./U2
6090 FW4=VW4*18.01*60./U2

```

Table 12 - continued

```

6100 F4=FC4+FH4+FW4
6110 CHWRT0=FC4/TH4
6120 HCVRT0=VH4/VC4
6130 P5=P7
6140 DP56=V5*(V5*C562+C561)
6150 P6=P5-DP56
6160 T6=(V5A*T6A+(V5-V5A)*T5)/V5
6170 IF(V1.LE.62.)PWRCTB=2.8*V1+153.8
6180 IF(V1.GT.62. .AND. V1.LE.65.)PWRCTB=40.*V1-2150.
6190 IF(V1.GT.65.)PWRCTB=-34.*V1+2660.
6200 T11=T2+PWRCTB*U3/(V1*CPA)
6210 V11=V2
6220 P11=P8
6230 PWRCLB=0.
6240 DP1213=C12132*V5*V5
6250 IF(V5.LT.1.01*V5MIN)GOTO14
6260 DP1213=C12132*V5MIN*V5MIN
6270 TR=(DP78/1.869+.05)/1.3
6280 TR=TR**(.128+.102*DP78/1.869)
6290 PWH=410.-.00396*(V5-368)**2
6300 PWL=410.-.00178*(V5-306. )**2
6310 PWRCLB=TR*PWH+(1.-TR)*PWL
6320 14CONTINUE
6330 P12=P8+DP1213
6340 T12=T6+PWRCLB*U3/(V5*CPA)
6350 T13=T12
6360 V12=V5
6370 P13=P8
6380 V13=V5
6390 V8=V10+V2+V5
6400 VW8=VW7+VW2-VW1
6410 VC8=VC7-VC4
6420 PC8=VC8*P8/V8
6430 VN8=VN7
6440 PN8=VN8*P8/V8
6450 V08=V07-.5*(VH3-VH4)
6460 PW8=P8*VW8/V8
6470 DW8=DEWT(PW8)
6480 T8=(T11*V11+T13*V13+T7*V10+POWER*U3/CPA)/V8
6490 RH8=100.*PW8/PHT0(T8)
6500 IF(KBASE.EQ.3)RETURN
6510 AV7=V7*(T7+460.)*1.434/P7
6520 AV1=V1*AV7/V7
6530 AV2=V2*(T2+460.)*1.434/P2
6540 AV11=V11*(T11+460.)*1.434/P11
6550 AV9=V9*(T9+460.)*1.434/P9
6560 AV3=V3*(T3+460.)*1.434/P3
6570 AV4=V4*(T4+460.)*1.434/P4
6580 AV5=V5*AV7/V7
6590 AV6=V5*(T6+460.)*1.434/P6

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continued-

Table 12 - continued

```

7100&"VN7",VN7,"DW7",DW7,"RH7",RH7
7110C
7120 WRITE(IOUT;1015)
7130 1015FORMAT(" PROCESS AIR OUTLET:")
7140 WRITE(IOUT;944)"P8 ",P8,"PC8",PC8,"V10",V10,"DP78",DP78,
7150&"V8 ",V8,"VW8",VW8,"VC8",VC8,"VO8",VO8,"PW8",PW8,"T8 ",T8,
7160&"DW8",DW8,"RH8",RH8
7170C
7180 WRITE(IOUT;1019)
7190 1019FORMAT(" H2 INLET:")
7200 WRITE(IOUT;944)"P9 ",P9,"PW9",PW9,"DP93",DP93,"P3 ",P3
7210&"PW3",PW3,"PH3",PH3,"V3 ",V3,"VH3",VH3,"VW3",VW3,"FH3",FH3,"V9MSL",V9MSL
7220C
7230 WRITE(IOUT;1013)
7240 1013FORMAT(" H2 OUTLET:")
7250 WRITE(IOUT;944)"P4 ",P4,"DP34",DP34,"PW4",PW4,"V4 ",V4,"VC4",VC4,
7260&"VH4",VH4,"VW4",VW4,"V4SL",V4SL,"VC4SL",VC4SL,"VH4SL",VH4SL,"F4 ",F4,
7270&"FC4",FC4,"FH4",FH4,"FW4",FW4,"DW4",DW4,"CHWRT0",CHWRT0,"HCVRT0",HCVRT0
7280C
7290 WRITE(IOUT;1023)
7300 1023FORMAT(" HEAT BALANCE, MODULES:")
7310 WRITE(IOUT;944)"HEATLD",HEATLD,"DHA",DHA,"DHH",DHH,"DHC",DHC
7320C
7330 WRITE(IOUT;1012)
7340 1012FORMAT(" COOLING AIR:")
7350 WRITE(IOUT;944)"P5 ",P5,"DP56",DP56,"P6 ",P6
7360&"V5 ",V5,"T5 ",T5,"T6 ",T6,"HC ",HC,"ETA",ETA
7370&"V5A",V5A,"T6A",T6A
7380&"P12",P12,"V12",V12,"T12",T12,"DP1213",DP1213,"V5MIN",V5MIN
7390C
7400 WRITE(IOUT;1041)
7410 1041FORMAT(" ACTUAL VOLUMETRIC FLOW RATES:")
7420 WRITE(IOUT;944)"AV1",AV1,"AV2",AV2,"AV3",AV3,"AV4",AV4,"AV5",AV5,
7430&"AV6",AV6,"AV6A",AV6A,"AV7",AV7,"AV8",AV8,"AV9",AV9,
7440&"AV10EX",AV10EX,"AV11",AV11,"AV12",AV12,"AV13",AV13
7450C
7460 WRITE(IOUT;1016)
7470 1016FORMAT(" EQUIVALENT WEIGHT:")
7480 WRITE(IOUT;944)"PWRCLB",PWRCLB,"PWRCTB",PWRCTB,"PWRPC",PWRPC,
7490&"PWREC",PWREC,"PWRDAU",PWRDAU,"PWRTOT",PWRTOT,"HTTOT",HTTOT,
7500&"PWRWGT",PWRWGT,"HTWGT",HTWGT,"H2OWGT",H2OWGT,"OXWGT",OXWGT,
7510&"HRDWGT",HRDWGT,"EQWGT",EQWGT
7520 RETURN
7530 END
7540C
7550 FUNCTIONPHTO(TF)
7560 DATA A,B,C,D,EE,F,G/3.2437814,.00586826,1.1702379E-8,
7570&.0021878462,5.219603,273.16,2.3025851/
7580 TC=(TF-32.)/1.8
7590 I=374.11-TC

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Table 12 - continued

```

7600 PHTO=EXP(G*(EE-(X/(TC+P))*(A+B*X+C*X**3)/(1.0+D*X)))
7610 RETURN
7620 END
7630C
7640 FUNCTION DEWT(P)
7650 EXTERNAL ROOT,PHTO
7660 XX=ALOG(P)
7670 TA=-2.4+20.25*XX+1.522*XX**2
7680 TB=TA+.1
7690 DEWT=ROOT(TA,TB,PHTO,P,.005,.005,5)
7700 RETURN
7710 END
7720C
7730 FUNCTION TICOR(PC,AF,CD,DEL)
7740 REAL S(5,7)
7750 DATA S/1.75187,-.511449,.0775073,-.00592584,.000179862,
7760& 1.42306,-.271935,.0210187,-.00034839,-1.8475E-5,
7770& 1.08190,-.110821,-.0081408,.00196359,-8.5832E-5,
7780& .90258,-.105068,.0025161,.00028694,-1.3673E-5,
7790& .71551,-.072213,.0024297,9.08E-6,-3.48E-7,
7800& .61612,-.055237,.0003803,.00028605,-1.5623E-5,
7810& .52087,-.035109,-.0014939,.00035115,-1.4808E-5/
7820 P=AMIN1(PC,10.)
7830 PA=P*(AF/.44)**((.84*P+1.)*EXP(-.84*P))
7840 J=CD/5.-1.
7850 IF(J.LT.1)J=1
7860 TI1=PA*(S(1,J)+PA*(S(2,J)+PA*(S(3,J)+PA*(S(4,J)+PA*S(5,J))))
7870 IF(J.LT.7)GO TO 8
7880 TICOR=TI1
7890 GOTO 9
7900 8 J=J+1
7910 TI2=PA*(S(1,J)+PA*(S(2,J)+PA*(S(3,J)+PA*(S(4,J)+PA*S(5,J))))
7920 AII=J
7930 TERP=CD/5.-AII
7940 TICOR=TI2*TERP+TI1*(1.-TERP)
7950 9 TICOR=TICOR*(1+.03536*(DEL-18.33))
7960 RETURN
7970 END
7980C
7990 FUNCTION ROOT(X1,X2,YFCN,W,XTOL,YTOL,K)
8000 COMMON IOUT
8010 EXTERNAL YFCN
8020 XA=X1
8030 XB=X2
8040 FA=YFCN(XA)-W
8050 FB=YFCN(XB)-W
8060 DO 91 IROOT=1,K
8070 ROOT=(FA*XB-FB*XA)/(FA-FB)
8080 FN=YFCN(ROOT)-W
8090 IF(ABS(FN).LT.YTOL .AND.

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Table 12 - continued

```

8100&ABS(ROOT-XB).LT.XTOL)RETURN
8110 IF(IROOT.GE.K)WRITE(IOUT;200)X1,X2,W,XTOL,YTOL,IROOT,
8120& XA,XB,ROOT,FA,FB,FN
8130 200 FORMAT( " NONCONVERGENCE IN ROOT",5G11.4,I3/7G11.4)
8140 XA=XB
8150 XB=ROOT
8160 FA=FB
8170 FB=FN
8180 91 CONTINUE
8190 RETURN
8200 END
8210C
8220 SUBROUTINE TDRIFT
8230 REAL N,I
8240 COMMON IOUT,CPA,CPH,N,V3,T5,T3,T1,BK(12),
8250&BLANK(16),NBLANK,
8260&PCO,I,V1,HEATLD,DHC,DHA,DHH,DTREQ,DTAVA,E,
8270&HC,ETA,T2,V5A,T6A
8280 EXTERNAL ERT,ROOT,ERT1
8290 ENTHPR=V1*CPA*T1+V3*CPH*T3
8300 T2HIGH=(ENTHPR+.99*HEATLD)/(V1*CPA+V3*CPH)
8310 T2LOW=(ENTHPR+V5A*CPA*T5+HEATLD)/(V1*CPA+V3*CPH+V5A*CPA)
8320 T2=T2HIGH
8330 DUMMY=ERT(V5A/N)
8340 T2=ROOT(T2HIGH,T2LOW,ERT1,0.,.005,.005,20)
8350 RETURN
8360 END
8370C
8380 FUNCTION ERT1(T)
8390 REAL N,I
8400 COMMON IOUT,CPA,CPH,N,V3,T5,T3,T1,BK(12),
8410&BLANK(16),NBLANK,
8420&PCO,I,V1,HEATLD,DHC,DHA,DHH,DTREQ,DTAVA,E,
8430&HC,ETA,T2,V5A,T6A
8440 E=.729-.22*ALOG(I)+.008*I+.005*(T-78.)
8450 HEATLD=N*I*(1.25-E)*3.419
8460 DHA=V1*CPA*(T-T1)
8470 DHH=V3*CPH*(T-T3)
8480 DHC=HEATLD-DHA-DHH
8490 T6A=T5+DHC/(V5A*CPA)
8500 DTREQ=DHC*(.376+3.876/(HC*ETA))/N
8510 IF(T6A.LT.T)GOTO 1086
8520 ERT1=-DTREQ
8530 RETURN
8540 1086 DTAVA=(T6A-T5)/ALOG((T-T5)/(T-T6A))
8550 ERT1=DTAVA-DTREQ
8560 RETURN
8570 END
8580C
8590 FUNCTION ERT(V)

```

Table 12 - continued

```

8600 REAL N,I
8610 COMMON IOUT,CPA,CPH,N,V3,T5,T3,T1,BK(12),
8620&BLANK(16),NBLANK,
8630&PC0,I,V1,HEATLD,DHC,DHA,DHH,DTREQ,DTAVA,E,
8640&HC,ETA,T2,V5A,T6A
8650 IF(V.LE.1.)HC=1.97*V**(.3333)
8660 IF(V.GT.1. .AND. V.LT.2.9883)HC=1.21+V*(.34+.42*V)
8670 IF(V.GE.2.9883 .AND. V.LE.4.)HC=2.*V
8680 IF(V.GT.4.)HC=2.639016*V**(.8)
8690 ETA=1.
8700 IF(V.GT..32194 .AND. V.LT.24.72)ETA=1.0644-.1135*SQRT(V)
8710 IF(V.GE.24.72)ETA=2.486/SQRT(V)
8720 T6A=T5+DHC/(V*CPA*N)
8730 DTREQ=DHC*(.376+3.876/(HC*ETA))/N
8740 IF(T6A.LT.T2)GO TO 86
8750 ERT=-DTREQ
8760 RETURN
8770 86 DTAVA=(T6A-T5)/ALOG((T2-T5)/(T2-T6A))
8780 ERT=DTAVA-DTREQ
8790 RETURN
8800 END
8810C
8820 SUBROUTINE T(VARNAM,VAR,BOT,TOP,I)
8830 COMMON IOUT
8840 IF(VAR.GE.BOT.AND.VAR.LE.TOP)RETURN
8850 WRITE(IOUT;10)VARNAM,VAR,BOT,TOP
8860 I=I+1
8870 RETURN
8880 10FORMAT(1X,A6,"=",G10.4," RANGE: ",2G10.4)
8890 END
8900C
8910 SUBROUTINE BMODE
8920 REAL N,I
8930 COMMON IOUT,CPA,CPH,N,V3,T5,T3,T1,BK(12),
8940&BLANK(16),NBLANK,PC0,I,V1
8950 I=BK(1)
8960 IF(PC0.LE.BK(2))GO TO 10
8970 I=BK(4)
8980 IF(PC0.GE.BK(3))GO TO 10
8990 I=BK(9)*PC0+BK(10)
9000 10 V1=BK(5)
9010 IF(PC0.LE.BK(6))RETURN
9020 V1=BK(8)
9030 IF(PC0.GE.BK(7))RETURN
9040 V1=BK(11)*PC0+BK(12)
9050 RETURN
9060 END

```

TABLE 13 CHECKS AND MESSAGES

1. CONDITION: An input variable is out of the prediction range.
 MESSAGE: VARIABLE = XX.XX RANGE: XX.XX XX.XX
2. CONDITION: Less than 1.3 times stoichiometric amount of H₂ is supplied.
 MESSAGE: INSUFFICIENT HYDROGEN. XXX.XX SLPM IS REQUIRED.
3. CONDITION: Cathode air blowers cannot supply the requested flow rate. Program sets the flow equal to blower capacity.
 MESSAGE: V1 HAS BEEN CHANGED TO 70 SCFM, BLOWER CAPACITY.
4. CONDITION: Not enough heat is generated in the modules to attain the setpoint module temperature.
 MESSAGE: COOLING BLOWERS ARE OFF. MODULE TEMPERATURE FALLS X.XXF BELOW THE DESIRED XX.XXF TO XX.XXF.
5. CONDITION: Process streams and cooling air cannot remove enough heat to maintain the setpoint module temperature.
 MESSAGE: COOLING BLOWERS ARE ON FULL. MODULE TEMPERATURE RISES X.XXF ABOVE THE DESIRED XX.XXF TO XX.XXF.
6. CONDITION: Normal heat balance is attained.
 MESSAGE: DESIRED MODULE TEMPERATURE IS MAINTAINED WITH COOLING BLOWERS AT PARTIAL CAPACITY.
7. CONDITION: Process air flow does not exceed cathode air plus cooling air flow by at least 5%.
 MESSAGE: INSUFFICIENT PROCESS AIR TO PREVENT BACKMIXING THROUGH PLENUM BYPASS.
8. CONDITION: Inlet process air moisture conditions are out of tolerance and will not support steady state cell operation.
 MESSAGE: INLET PROCESS AIR DEW POINT DEPRESSION OUT OF RANGE. ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.
9. CONDITION: Outlet process air moisture conditions are out of tolerance and will not support steady state cell operation.
 MESSAGE: OUTLET PROCESS AIR DEW POINT DEPRESSION OUT OF RANGE. ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.

Table 13 - continued

10. CONDITION: Average of inlet and outlet process air moisture condition is out of tolerance and will not support steady state cell operation.
- MESSAGE: AVERAGE PROCESS AIR DEW POINT DEPRESSION OUT OF RANGE.
 ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.
11. CONDITION: Convergence subroutine (ROOT) did not approach a solution within the specified number of iterations.
- MESSAGE: NONCONVERGENCE IN ROOT (PRINT ROOT PARAMETERS)

TABLE 14 NOMENCLATURE AND UNITS

Composite Variable Names

First Prefix	P - (Partial) Pressure, mm Hg V - Volume Flow Rate, Scfm 70F, 760 mm Hg AV - Volume Flow Rate, Cfm F - Mass Flow Rate, Lb/Hr DP - Pressure Drop DW - Dew Point, F T - Temperature, F RH - Relative Humidity, %
Second Prefix	C - Carbon Dioxide (CO ₂) O - Oxygen (O ₂) N - Nitrogen (N ₂) H - Hydrogen (H ₂) W - Water (H ₂ O) (None) - Total Stream
Stream Number	Ø - Cabin Atmosphere 1 - Cathode Air Modules Inlet 2 - Cathode Air Modules Outlet 3 - H ₂ Modules Inlet 4 - H ₂ Modules Outlet 5 - Cooling Air Inlet 5A - Cooling Air Inlet, Active Cells 6 - Cooling Air Outlet 6A - Cooling Air Outlet, Active Cells 7 - Process Air Inlet 8 - Process Air Outlet 9 - H ₂ System Inlet 1Ø - Plenum Bypass 11 - Cathode Blowers Outlet 12 - Cooling Blowers Outlet 13 - Cooling Dampers Outlet
Units Suffix	(None) - Units of First Prefix PSA - Psia PSG - Psig SL - Slpm

Additional Variable Names

A,B,C,D,EE,F,G	Constants in pH ₂ O Dew Point Equation
All,J	Indices Determine S Constants
CD	Current Density
CHWRT0	CO ₂ /H ₂ Weight Ratio, Lb CO ₂ /Lb H ₂

continued-

Table 14 - continued

CJKN

Coefficient in Pressure Drop Equation

J = Inlet Stream Subscript

K = Outlet Stream Subscript

N = Degree of Term

COR34,COR93

 ΔP Correction Factors for Absolute Pressure

CPA

Volumetric Specific Heat, Air, Btu/Hr-Scfm-F

CPH

Volumetric Specific Heat, H_2 , Btu/Hr-Scfm-F

CTRANS

 CO_2 Transferred, Lb/Hr

CURDEN

Current Density, A/Ft²

DELT1

Input Control Variable = T2-DP1, F

DELT1P

Preferred Value Control Variable = T2-DP1, F

DELIE

Actual Control Variable = T2-DP1, F

DHA

Enthalpy Gain of Inlet Process Air, Btu/Hr

DHC

Enthalpy Gain of Cooling Air, Btu/Hr

DHH

Enthalpy Gain of Inlet H_2 , Btu/Hr

DDP1,DDP2

Dew Point Depression, Streams 1 and 2

DPTDAV

Process Air Dew Point Depression, Average, F

DROP,RISE

T2-(DWI + DELT1), Absolute Value of Module

Temperature Offset

DTAVA

Log Mean Available Temperature Drop, F

DTREQ

Required Module - Cooling Air Temperature Drop, F

E

Cell Voltage, Volt

EMOD

Module (16 Cells) Voltage

EQWGT

Total System Equation Weight

ERT,ERT1

Difference Between DTREQ and DTAVA

ESTACK

Stack Voltage, Volt

ETA

Cooling Fin Efficiency, Dimensionless, 0-1

FA,FB,FN

Dependent Values Corresponding to XA,XB,XN

FNAME

Variable Equal to Output File Name

HC

Cooling Fin Heat Transfer Coefficient,
Btu/Hr-Ft²-F

HCON

 H_2 Consumption, Lb/Hr

HCVRTO

 H_2/CO_2 Volume Ratio, Scfm H_2 /Scfm CO_2

HEATLD

Net Heat Produced, Btu/Hr

HTPEN

Heat Rejection Penalty, Lb/Btu/Hr

HTTOT

Total Heat Rejection

HTWGT

Heat Rejection Penalty Weight

H2OPEN

 H_2O Vapor Rejection Penalty, Lb/Lb/Hr

H2OWGT

 H_2O Rejection Penalty Weight

I

Current, Amp

INP

Input Device Code: 2=File, 50=Terminal

IOUT

Output Device Code: 1=File, 66=Terminal

MATHIN

Name of Input Data File

N

Number of Cells in Circuit

NERROR

Check Violation Indicator

0 - No Violation

1 - Violation

continued-

Table 14 - continued

NFLAG,FLAG	Program Option Integer = 0 or 1
OCON	O ₂ Consumption, Lb/Hr
OXPEN	O ₂ Consumption Penalty, Lb/Lb/Hr
OXWGT	O ₂ Consumption Penalty Weight
P	Inlet pCO ₂
PA	Inlet pCO ₂ Corrected for Effect of Air Flow
POWER	Electrical Power Produced, Watt
PWPEN	Power Penalty, Lb/Watt
PWRCLB	Cooling Blower Power, Watt
PWRCTB	Cathode Blower Power, Watt
PWRDAU	Data Acquisition Unit Power, Watt
PWREC	Emergency Controller Power, Watt
PWRPC	Primary Controller Power, Watt
PWRTOT	Total Power, Watt
PWRWGT	Power Penalty Weight
QA,QB,QC	Coefficients of V5 in Quadratic Formula
S	Array containing Coefficients of PA in TI Correlation
TA,TB	Trial Values of Dew Point, F
TC,TF	Dew Point, C, F, respectively
TE	Current Efficiency, %
TERP	Current Density Interpolation Variable
TI	Transfer Index, Lb CO ₂ /Lb O ₂
T2INP	Set Point Value of T2
T2P	Preferred Value of T2
T11	TI at one of the seven current densities just below the desired current density
T12	TI at one of the seven current densities just above the desired current density
U1	Conversion Factor, mm Hg/Psi
U2	Conversion Factor, Scf/Lb Mol
U3	Conversion Factor, Btu/Hr-Watt
U4	Conversion Factor, 1/Ft ³
V,TR	Dummy and Interpolation Variables
VA,VB	Trial Values for V5
V5INP	Cooling Flow for Set Point Module Temperature
V5MIN	Cooling Flow with Blowers Off
V7M1	Plenum Inlet Flow less Cathode Air Flow
V9MSL	Minimum Flow of H ₂ Required
WPROD	Water Production, Lb/Hr
X1,X2,XA,XB,XN	Trial Values of Independent Variable in Subroutine Root

Additional Variables, Main Program Only

AØ	Output Variable Array
AVG	Array Containing Average TAB Values
BK	Mode B Parameters
CGEN	Numeric Array, CO ₂ Generation Rates, Lb/Hr

continued-

Table 14 - continued

HEAD	Alphabetic Constant Array, Containing Output Variable Names
HDG	Array Containing Selected Values of HEAD
IGEN	CO ₂ Generation Step Subscript
INDEX	Subscripts of Selected Output Variables
IR	Out-of-Range Input Variable Counter
KBASE	Variable Indicating Range of BASE to be Executed
KERROR	Non-Steady State Indicator
KMODE	Mode Indicator, 0=Mode A, 1=Mode B
KPRINT,NPRINT, DPRINT,QPRINT	Output Indicators
MINCYC	Length of One Cycle, Min
NDAY	Day Counter
NDT,DT	Integration Increment, Min
NDAYS,DAYS	Maximum Number of Days to be Simulated
NDEX	Number of Selected Output Variables
NSTEPS	Number of Steps in CO ₂ Generation Table
NT	Time, Min
QC02GT	New CO ₂ Generation Table Indicator
QFIN	File Input Indicator
QFOUT	File Output Indicator
QPRINT	Base Program Output Table Indicator
QSUBS	New Subscript Indicator
SAME	Dummy File Name to Prevent Closing Output File
SLOPE,SLOPEA, SLOPEB,SLOPEC	pCO ₂ Rate of Change, mm Hg/Min
TAB	Array Containing Selected Values of A ₀
TMAX	Ending Times for CO ₂ Generation Rates, Min
U5	Conversion Factor, $\frac{\text{mm Hg/Min}}{\text{Lb/Hr}}$
XA,YA,XB,YB,XC,YC	Successive Values of Cabin pCO ₂ Approximation and Error

TABLE 15 KEY TO SELECTIVE OUTPUT VARIABLES

AV1	130	FC1	86	RH8	129
AV10EX	140	FC2	94	SLOPEC	29
AV11	141	FC4	104	T11	114
AV12	142	FH3	89	T12	118
AV13	143	FH4	105	T2	13
AV2	131	FW1	87	T2P	80
AV3	132	FW2	95	T6	112
AV4	133	FW4	106	T6A	15
AV5	134	H2OWGT	148	T8	128
AV6	135	HC	11	TE	92
AV6A	136	HCON	53	TI	50
AV7	137	HCVRT0	109	V1	3
AV8	138	HEATLD	4	V10	32
AV9	139	HTTOT	145	V2	73
CHWRT0	108	HTWGT	147	V4	100
CO2GEN	30	I	2	V4SL	101
COR34	33	OCON	51	V5	20
COR93	37	OXWGT	149	V5A	14
CTTRANS	52	P1	45	V5INP	31
CURDEN	47	P12	117	V5MIN	19
DDP1	76	P2	46	V7M1	18
DDP2	77	P3	35	V8	119
DELT1	16	P3PSA	36	V9MSL	17
DELT1E	48	P6	111	VC1	70
DELT1P	79	P7	42	VC2	72
DHA	6	P7PSA	43	VC4	55
DHC	5	P9	39	VC4SL	102
DHH	7	P9PSA	40	VC7	81
DP12	44	PC0	1	VC8	121
DP1213	115	PC1	49	VH3	58
DP34	34	PC2	93	VH4	59
DP56	110	PC8	122	VH4SL	103
DP78	41	PH3	88	VN1	68
DP93	38	PN1	67	VN7	84
DPTDAV	78	PN8	124	VN8	123
DTAVA	9	P00	65	V01	69
DTREQ	8	P07	66	V02	71
DUM1	21	POWER	91	V07	83
DUM2	22	PW1	60	V08	125
DUM3	23	PW2	74	VW1	61
DUM4	24	PW3	57	VW2	64
DUM5	25	PW4	98	VW3	62
DW2	75	PW8	126	VW4	99
DW4	97	PW9	56	VW7	82
DW8	127	PWRCLB	116	VW8	120
E	10	PWRCTB	113	VWPROD	63
EMOD	90	PWRTOT	144	WPROD	54
EQWGT	150	PWRWGT	146	YA	26
ETA	12	RH2	96	YB	27
F4	107	RH7	85	YC	28

continued-

Table 15 - continued

1	PC0	51	OCON	101	V4SL
2	I	52	CTTRANS	102	VC4SL
3	V1	53	HCON	103	VH4SL
4	HEATLD	54	WPROD	104	FC4
5	DHC	55	VC4	105	FH4
6	DHA	56	PW9	106	FW4
7	DHH	57	PW3	107	F4
8	DTREQ	58	VH3	108	CHWRT0
9	DTAVA	59	VH4	109	HCVRT0
10	E	60	PW1	110	DP56
11	HC	61	VW1	111	P6
12	ETA	62	VW3	112	T6
13	T2	63	VWPROD	113	PWRCTB
14	V5A	64	VW2	114	T11
15	T6A	65	P00	115	DP1213
16	DELT1	66	P07	116	PWRCLB
17	V9MSL	67	PN1	117	P12
18	V7M1	68	VN1	118	T12
19	V5MIN	69	VO1	119	V8
20	V5	70	VC1	120	VW8
21	DUM1	71	VO2	121	VC8
22	DUM2	72	VC2	122	PC8
23	DUM3	73	V2	123	VN8
24	DUM4	74	PW2	124	PN8
25	DUM5	75	DW2	125	VO8
26	YA	76	DDP1	126	PW8
27	YB	77	DDP2	127	DW8
28	YC	78	DPTDAV	128	T8
29	SLOPEC	79	DELT1P	129	RH8
30	CO2GEN	80	T2P	130	AV1
31	V5INP	81	VC7	131	AV2
32	V10	82	VW7	132	AV3
33	COR34	83	VO7	133	AV4
34	DP34	84	VN7	134	AV5
35	P3	85	RH7	135	AV6
36	P3PSA	86	FC1	136	AV6A
37	COR93	87	FW1	137	AV7
38	DP93	88	PH3	138	AV8
39	P9	89	PH3	139	AV9
40	P9PSA	90	EMOD	140	AV10EX
41	DP78	91	POWER	141	AV11
42	P7	92	TE	142	AV12
43	P7PSA	93	PC2	143	AV13
44	DP12	94	FC2	144	PWRTOT
45	P1	95	FW2	145	HTTOT
46	P2	96	RH2	146	PWRWGT
47	CURDEN	97	DW4	147	HTWGT
48	DELT1E	98	PW4	148	H2OWGT
49	PC1	99	VW4	149	OXWGT
50	TI	100	V4	150	EQWGT

APPENDIX D CS-6 CABIN pCO₂ SIMULATION PROGRAM SAMPLE OUTPUTS

<u>TABLE</u>		<u>PAGE</u>
1	Output Examples	D-2

TABLE 1 OUTPUT EXAMPLES

```

**** MODE B ZERO TO STEADY STATE PCO2 LIMITS 1 & 2 MMHG ****
*****INPUT DATA*****
CABIN ATMOSPHERE:
  POPSA      14.70 ! PCO      0.1000E-02 ! POOPSA      3.100 ! TO      70.00
  VOLUME      8000. !
PROCESS AIR OUTLET/INLET:
  POPSA      14.75 ! T7      55.00 ! V7      265.0 ! DW7      50.00
H2 OUTLET/INLET:
  P4PSA      20.00 ! T9      72.00 ! V9SL      10.00 ! DW9      69.00
MODULES:
  N          96.00 ! I          2.586 ! DELT1      22.00 ! V1      20.00
PENALTY WEIGHT FACTORS:
  PWPEN      0.5910 ! HTPEN      0.1280 ! H2OPEN      134.0 ! OXPEN      1536.
CONTROL:
  KMODE      1.000 ! NFLAG      1.000 ! IMIN      2.586 ! PCIMIN      1.000
  PCIMAX      2.000 ! IMAX      6.600 ! VMIN      20.00 ! PCVMIN      1.000
  PCVMAX      2.000 ! VMAX      60.00 ! DAYS      10.00 ! DT      15.00
  DPRINT      60.00 !

*****RESULTS*****
PREFERRED VALUE OF DELT1 IS 23.58 UNDER THESE CONDITIONS
SO THAT 73.58 = T2 = DW1 + DELT1 = 50.00 + 23.58.
MODULES:
  TI      0.8810E-03 ! TE      0.3204E-01 ! E      0.5038 ! EMOD      8.061
  CTRANSO.1439E-03 ! OCON      0.1634 ! HCON      0.2058E-01 ! WPROD      0.1839
  CURDEN      10.60 ! HEATLD      633.3 ! POWER      125.1 !
CATHODE AIR INLET:
  P1      763.6 ! PC1      0.1004E-02 ! PW1      9.212 ! FC1      0.1797E-03
  FW1      0.6742 ! VC1      0.2632E-04 ! VW1      0.2413 ! V01      4.218
  VN1      15.54 ! T1      55.00 ! DW1      50.00 ! RH1      83.20
CATHODE AIR OUTLET:
  P2      761.9 ! DP12      1.737 ! PC2      0.1992E-03 ! PW2      11.73
  V2      20.03 ! VC2      0.5239E-05 ! VW2      0.3083 ! V02      4.185
  VN2      15.54 ! FC2      0.3577E-04 ! FW2      0.8616 ! T2      70.64
  DW2      56.58 ! RH2      61.11 ! P11      762.6 ! V11      20.03
  T11      104.0 !
PROCESS AIR INLET:
  P7      763.6 ! PW7      9.212 ! PN7      593.4 ! VC7      0.3487E-03
  VW7      3.197 ! V07      55.88 ! VN7      205.9 ! DW7      50.00
  RH7      83.20 !
PROCESS AIR OUTLET:
  P8      762.6 ! PC8      0.9426E-03 ! V10      215.7 ! DP78      1.047
  V8      265.0 ! VW8      3.264 ! VC8      0.3276E-03 ! V08      55.85
  PW8      9.391 ! T8      61.24 ! DW8      50.52 ! RH8      67.80

```

continued-

Table 1 continued

H2 INLET:

P9	1157.	!	PW9	18.15	!	DP93	120.3	!	P3	1037.
PW3	16.26	!	PH3	1021.	!	V3	0.3531	!	VH3	0.3476
VW3	0.5537E-02	!	FH3	0.1087	!	V9MSL	2.423	!		

H2 OUTLET:

P4	1034.	!	DP34	2.890	!	PW4	12.02	!	V4	0.2851
VC4	0.2108E-04	!	VH4	0.2818	!	VW4	0.3315E-02	!	V4SL	8.074
VC4SL	0.5969E-03	!	VH4SL	7.980	!	F4	0.9755E-01	!	FC4	0.1439E-03
FH4	0.8814E-01	!	FW4	0.9264E-02	!	DW4	57.28	!	CHWRT00	0.1633E-02
HCVRT00	0.1337E+05	!								

HEAT BALANCE, MODULES:

HEATLD	633.3	!	DHA	336.6	!	DHH	-5140	!	DHC	297.2
--------	-------	---	-----	-------	---	-----	-------	---	-----	-------

COOLING AIR:

P5	763.6	!	DP56	0.3072	!	P6	763.3	!	V5	29.31
T5	55.00	!	T6	64.42	!	HC	1.327	!	ETA	1.000
V5A	29.31	!	T6A	64.42	!	P12	763.3	!	V12	29.31
T12	64.42	!	DP1213	0.7396	!	V5MIN	29.31	!		

ACTUAL VOLUMETRIC FLOW RATES:

AV1	19.34	!	AV2	20.01	!	AV3	0.2598	!	AV4	0.2098
AV5	28.34	!	AV6	28.87	!	AV6A	28.87	!	AV7	256.3
AV8	259.8	!	AV9	0.2328	!	AV10EX	208.9	!	AV11	21.25
AV12	28.87	!	AV13	28.90	!					

EQUIVALENT WEIGHT:

PWRCLB	0.0000	!	PWRCTB	209.8	!	PWRPC	136.0	!	PWREC	45.00
PWRDAU	100.0	!	PWRTOT	490.8	!	HTTOT	2739.	!	PWRWGT	290.1
HTWGT	350.6	!	H2OWGT	24.65	!	OXWGT	250.9	!	HRDWGT	817.9
EQWGT	1734.	!								

*****DAY 1 *****

TIME

PCO	I	V1	TI	OC ON	CTrans	EQWGT
-----	---	----	----	-------	--------	-------

0: 0						
0.1000E-02	2.586	20.00	0.8810E-03	0.1634	0.1439E-03	1734.
1: 0						
0.2788	2.586	20.00	0.2408	0.1634	0.3933E-01	1734.
2: 0						
0.5259	2.586	20.00	0.4545	0.1634	0.7425E-01	1734.
3: 0						
0.7451	2.586	20.00	0.6490	0.1634	0.1060	1734.
4: 0						
0.9391	2.586	20.00	0.8246	0.1634	0.1347	1734.

continued -

Table 1 continued

5: 0	1.098	2.979	23.92	1.979	0.1882	0.2031	1808.
6: 0	1.196	3.373	27.84	1.236	0.2131	0.2633	1903.
7: 0	1.265	3.652	30.62	1.337	0.2307	0.3084	1980.
8: 0	1.444	4.367	37.75	1.513	0.2759	0.4174	2197.
9: 0	1.659	5.232	46.36	1.650	0.3305	0.5452	2458.
10: 0	1.794	5.775	51.78	1.684	0.3648	0.6145	2605.
11: 0	1.886	6.141	55.43	1.687	0.3879	0.6546	2700.
12: 0	1.922	6.286	56.87	1.688	0.3971	0.6703	2736.
13: 0	1.823	5.890	52.92	1.687	0.3721	0.6275	2635.
14: 0	1.782	5.726	51.29	1.683	0.3617	0.6087	2592.
15: 0	1.822	5.887	52.89	1.687	0.3719	0.6272	2634.
16: 0	1.905	6.219	56.20	1.688	0.3928	0.6631	2719.
17: 0	1.963	6.451	58.51	1.686	0.4075	0.6872	2777.
18: 0	1.948	6.392	57.93	1.687	0.4038	0.6813	2763.
19: 0	1.842	5.964	53.66	1.687	0.3768	0.6357	2654.
20: 0	1.795	5.777	51.79	1.684	0.3649	0.6146	2605.
21: 0	1.817	5.867	52.69	1.686	0.3706	0.6250	2629.
22: 0	1.818	5.869	52.71	1.686	0.3707	0.6252	2630.
23: 0	1.740	5.556	49.60	1.675	0.3510	0.5880	2547.
24: 0	1.590	4.955	43.60	1.616	0.3130	0.5057	2380.
AVERAGES:	1.501	4.910	43.16	1.400	0.3102	0.4724	2361.

continued -

Table 1 - continued

*****DAY 2*****

TIME	PCO	I	V1	TI	OC ON	CTrans	BWGt

0: 0	1.590	4.955	43.60	1.616	0.3130	0.5057	2380.
1: 0	1.490	4.552	39.59	1.549	0.2875	0.4453	2259.
2: 0	1.429	4.309	37.17	1.501	0.2722	0.4086	2178.
3: 0	1.393	4.163	35.71	1.469	0.2630	0.3863	2132.
4: 0	1.371	4.075	34.84	1.449	0.2574	0.3730	2104.
5: 0	1.358	4.023	34.32	1.436	0.2541	0.3650	2088.
6: 0	1.350	3.991	34.00	1.429	0.2521	0.3602	2079.
7: 0	1.357	4.019	34.28	1.435	0.2539	0.3644	2087.
8: 0	1.499	4.587	39.94	1.555	0.2898	0.4507	2271.
9: 0	1.693	5.367	47.71	1.662	0.3390	0.5635	2495.
10: 0	1.817	5.864	52.66	1.686	0.3704	0.6246	2628.
11: 0	1.901	6.203	56.04	1.688	0.3913	0.6614	2715.
12: 0	1.933	6.329	57.30	1.688	0.3998	0.6748	2747.
13: 0	1.831	5.920	53.22	1.687	0.3740	0.6309	2643.
14: 0	1.787	5.746	51.49	1.683	0.3630	0.6111	2597.
15: 0	1.826	5.901	53.03	1.687	0.3728	0.6288	2638.
16: 0	1.907	6.229	56.30	1.688	0.3935	0.6642	2722.
17: 0	1.965	6.458	58.58	1.686	0.4079	0.6879	2779.
18: 0	1.949	6.397	57.98	1.687	0.4041	0.6813	2764.
19: 0	1.842	5.967	53.70	1.687	0.3770	0.6361	2655.
20: 0	1.795	5.779	51.82	1.684	0.3651	0.6149	2606.

continued -

Table 1 continued

21: 0							
1.818	5.868	52.71	1.686	0.3707	0.6251	2620.	
22: 0							
1.818	5.870	52.72	1.686	0.3708	0.6253	2630.	
23: 0							
1.740	5.557	49.61	1.675	0.3510	0.5881	2547.	
24: 0							
1.590	4.955	43.61	1.616	0.3130	0.5058	2380.	
AVERAGES:							
1.686	5.339	47.43	1.613	0.3372	0.5491	2474.	

*****INPUT DATA*****

CABIN ATMOSPHERE:

POPSA	14.70	!	PCO	10.00	!	POOPSA	3.100	!	TO	70.00
VOLUME	8000.	!								

PROCESS AIR OUTLET/INLET:

PSPSA	14.75	!	T7	55.00	!	V7	265.0	!	DW7	50.00
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H2 OUTLET/INLET:

P4PSA	20.00	!	T9	72.00	!	V9SL	10.00	!	DW9	69.00
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MODULES:

N	96.00	!	I	6.600	!	DELT1	22.00	!	V1	60.00
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PENALTY WEIGHT FACTORS:

PWPEN	0.5910	!	HTPEN	0.1280	!	H2OPEN	134.0	!	OXPEN	1536.
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CONTROL:

KMODE	1.000	!	NFLAG	1.000	!	IMIN	2.586	!	PCIMIN	2.500
PCIMAX	2.800	!	IMAX	6.600	!	VMIN	20.00	!	PCVMIN	2.500
PCVMAX	2.800	!	VMAX	60.00	!	DAYS	10.00	!	DT	15.00
DPRINT	60.00	!								

*****RESULTS*****

continued -

Table 1 continued

*****DAY 1*****

TIME	PCO	I	V1

0: 0			
10.00	6.600	60.00	
1: 0			
9.318	6.600	60.00	
2: 0			
8.641	6.600	60.00	
3: 0			
7.967	6.600	60.00	
4: 0			
7.300	6.600	60.00	
5: 0			
6.642	6.600	60.00	
6: 0			
5.999	6.600	60.00	
7: 0			
5.388	6.600	60.00	
8: 0			
4.968	6.600	60.00	
9: 0			
4.712	6.600	60.00	
10: 0			
4.471	6.600	60.00	
11: 0			
4.246	6.600	60.00	
12: 0			
4.008	6.600	60.00	
13: 0			
3.645	6.600	60.00	
14: 0			
3.344	6.600	60.00	
15: 0			
3.149	6.600	60.00	
16: 0			
3.037	6.600	60.00	
17: 0			
2.936	6.600	60.00	
18: 0			
2.786	6.415	58.16	
19: 0			
2.623	4.232	36.41	

continued -

Table 1 - continued

20: 0			
	2.599	3.912	33.21
21: 0			
	2.628	4.292	37.00
22: 0			
	2.622	4.219	36.27
23: 0			
	2.573	3.556	29.67
24: 0			
	2.513	2.764	21.78
AVERAGES:			
	4.620	5.953	53.55

*****DAY 2 *****

TIME	PCO	I	V1
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0: 0			
	2.513	2.764	21.78
1: 0			
	2.505	2.660	20.73
2: 0			
	2.505	2.649	20.63
3: 0			
	2.505	2.648	20.62
4: 0			
	2.505	2.648	20.62
5: 0			
	2.505	2.648	20.62
6: 0			
	2.505	2.648	20.62
7: 0			
	2.514	2.776	21.89
8: 0			
	2.599	3.909	33.18
9: 0			
	2.670	4.861	42.67
10: 0			
	2.688	5.104	45.09
11: 0			
	2.694	5.188	45.93
12: 0			
	2.672	4.882	42.88
13: 0			
	2.593	3.825	32.35

continued -

Table 1 - continued

14: 0		
2.593	3.829	32.38
15: 0		
2.635	4.388	37.95
16: 0		
2.678	4.972	43.77
17: 0		
2.691	5.141	45.46
18: 0		
2.657	4.682	40.89
19: 0		
2.589	3.783	31.93
20: 0		
2.592	3.820	32.30
21: 0		
2.626	4.273	36.31
22: 0		
2.622	4.215	36.23
23: 0		
2.572	3.556	29.66
24: 0		
2.513	2.764	21.78
AVERAGES:		
2.593	3.827	32.37